NASA TECHNICAL NOTE

NASA TN D-6432

NASA TN D-6432

MOTION CUE AND SIMULATION FIDELITY ASPECTS OF THE VALIDATION OF A GENERAL PURPOSE AIRBORNE SIMULATOR

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1971

1. Report No. NASA TN D-6432	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MOTION CUE AND SIMULATION FIDELITY ASPECTS OF THE VALIDATION OF A GENERAL PURPOSE AIRBORNE SIMULATOR		5. Report Date October 1971
		6. Performing Organization Code
7. Author(s) Kenneth J. Szalai		8. Performing Organization Report No. H-648
		10. Work Unit No. 720-06-00-01-24
9. Performing Organization Name and Address NASA Flight Research Center P. O. Box 273 Edwards, California 93523		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

In the validation of the general purpose airborne simulator, certain motion and visual cues could not be duplicated because the airborne simulator could not be independently controlled in six degrees of freedom. According to pilot opinion (NASA TN D-6431), however, the XB-70 airplane at two flight conditions had been simulated satisfactorily. Because of the dependence of simulation results on simulator configuration, two areas were investigated after the validation program was completed. The first was the effect of mismatched cues on observed handling qualities. Experiments which varied lateral acceleration at the pilot's location and yaw rate, while keeping constant the lateral-directional dynamics displayed on the pilot's instruments, showed pilot sensitivity to directional motion cues to be different for the simulation of two XB-70 flight conditions. A technique for allowing consecutive evaluations of moving- and fixed-base configurations in flight was used successfully to determine motion cue effects.

The second area investigated was the measurement and description of simulation fidelity. In-flight frequency-response measurements of the model-following system were taken to examine model-following fidelity for directly matched variables such as sideslip and roll rate as well as uncontrolled parameters such as lateral acceleration.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Simulation, motion cues, simulator validation, airborne simulation	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	35	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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INTRODUCTION

The NASA general purpose airborne simulator (GPAS), a modified Lockheed JetStar airplane, was validated by comparing pilot comments, ratings, and flight time histories obtained from the XB-70 airplane and the GPAS simulating the XB-70 airplane. Reference 1, which treated the handling-qualities results of the validation program, showed the GPAS to be capable of accurate and realistic simulation of the XB-70 airplane at two cruise flight conditions, Mach 1.2 at 12,192 meters (40,000 feet) altitude and Mach 2.35 at 16,764 meters (55,000 feet) altitude.

Motion and visual cue influences are critical in any simulator validation, especially in the analysis of pilot-noted discrepancies in the flying qualities of the simulator compared with the actual aircraft. Two major causes of such discrepancies are inaccuracies in the aerodynamic data and distortion due to the motion system. In the GPAS validation program (ref. 1), experiments were conducted to determine the sensitivity of the pilot to certain motion cues which were not being duplicated exactly, in order to assess the influence of these mismatched cues. The results of the experiments are presented in this report.

The selection of a simulator configuration and the operational experience with the model-following type of simulation are also pertinent to the validation results. The dynamic characteristics of the combined analog model/JetStar system are determined by the particular combination of feedback loops and control gains used. The methods used to configure the simulator and measure the resultant dynamics are discussed herein.

In general, this report supports and supplements the primary validation results of reference 1. The two reports comprise the GPAS validation documentation.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U. S. Customary Units. The measurements were taken in U. S. Customary Units. Factors relating the two systems are presented in reference 2.

F_a	pilot-applied aileron force, N (lb)

F_e	pilot-applied elevator force, N (lb)
F_r	pilot-applied rudder force, N (lb)
g	acceleration of gravity, m/sec^2 (ft/sec^2)
l_p	distance from center of gravity to pilot's station, m (ft)
M	Mach number
n_{y_p}	acceleration at pilot's location along Y-axis, g
n_{z_p}	acceleration at pilot's location along Z-axis, g
p	rolling angular velocity, deg/sec
r	yawing angular velocity, deg/sec
t	time, sec
V	true airspeed, m/sec (ft/sec)
X, Y, Z	coordinate-system axes (X, wind, positive forward; Y, body, positive toward right wing; Z, body, positive downward)
Y_β	dimensional side-force coefficient
α	angle of attack, deg
$\frac{\alpha_c}{\alpha_m}, \frac{\varphi_c}{\varphi_m}, \ldots$	input gains to model-controlled system
β	angle of sideslip, deg
$\dot{\beta}_s$	synthesized $\dot{\beta}$ signal, deg/sec
Δ	incremental change
δ_a	total aileron deflection, $(\delta_a)_{left} - (\delta_a)_{right}$, positive for left aileron trailing edge down, deg
δ_{a_p}	pilot's aileron command, positive when commanding positive δ_a, deg
δ_e	elevator deflection, positive for trailing edge down, deg
δ_{e_p}	pilot's elevator command, positive when commanding positive δ_e, deg

δ_r	rudder deflection, positive for trailing edge left, deg
δ_{r_p}	pilot's rudder command, positive when commanding positive δ_r, deg
$\epsilon_{( )}$	error in subscripted quantity
ζ	damping ratio
τ_r	roll-mode time constant, sec
τ_s	spiral-mode time constant, sec
φ	bank angle, deg
ω	frequency, rad/sec or Hz
(ω)	function of frequency
ω_{sp}	short-period undamped natural frequency, rad/sec
$\frac{\omega_\varphi}{\omega_\psi}$	handling-qualities parameter
ω_ψ	Dutch roll mode undamped natural frequency, rad/sec

Subscripts:

c	command, usually to an actuator
J	JetStar
m	model, analog computer quantity
sp	longitudinal short-period mode
ψ	Dutch roll mode

A dot over a quantity indicates differentiation with respect to time.

GENERAL PURPOSE AIRBORNE SIMULATOR

The GPAS was designed and fabricated under a NASA contract to the Cornell Aeronautical Laboratory (refs. 3 and 4). The layout of GPAS systems in the JetStar is shown in figure 1. This airborne simulator utilizes the model-controlled system (MCS) form of simulation. A simplified block diagram of the principal components of a typical MCS channel is shown in figure 2. The pilot's control inputs are routed to the airborne analog computer by means of an artificial feel system. The computer is programed with the equations of motion and aerodynamic characteristics of the aircraft

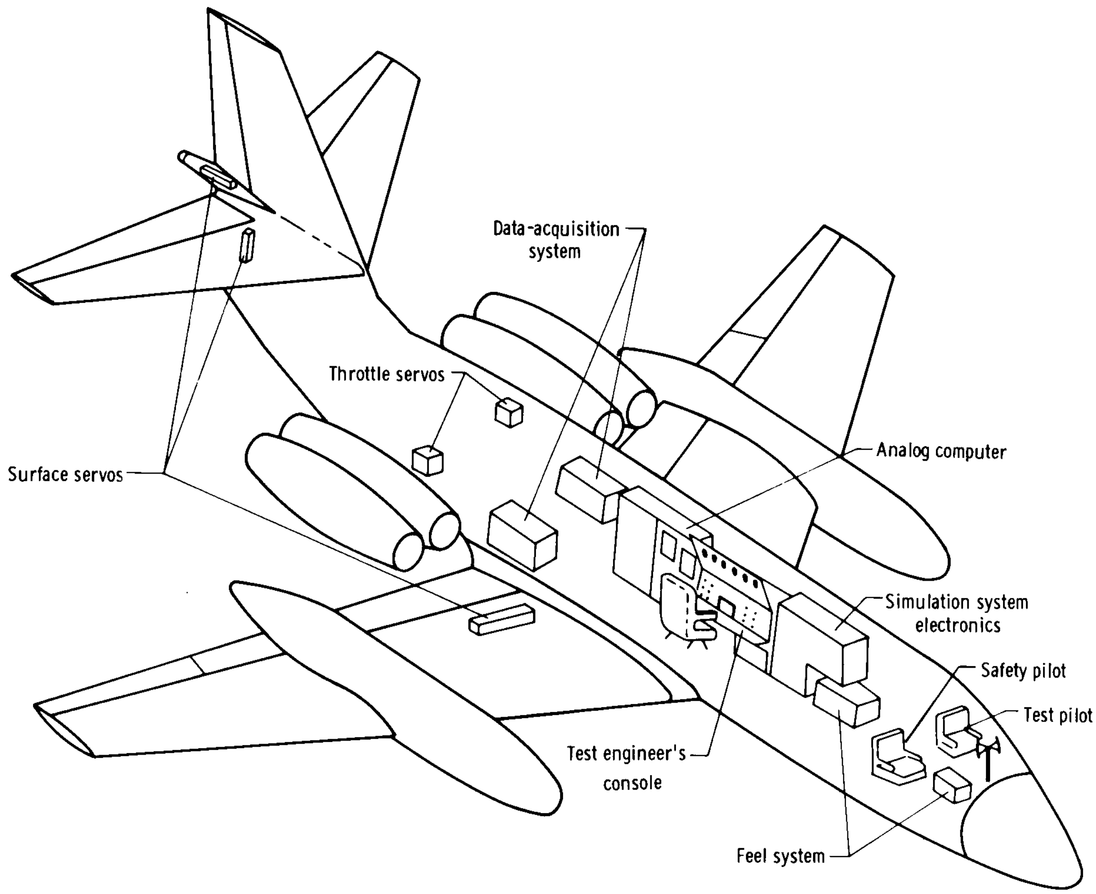


Figure 1. Layout of JetStar systems.

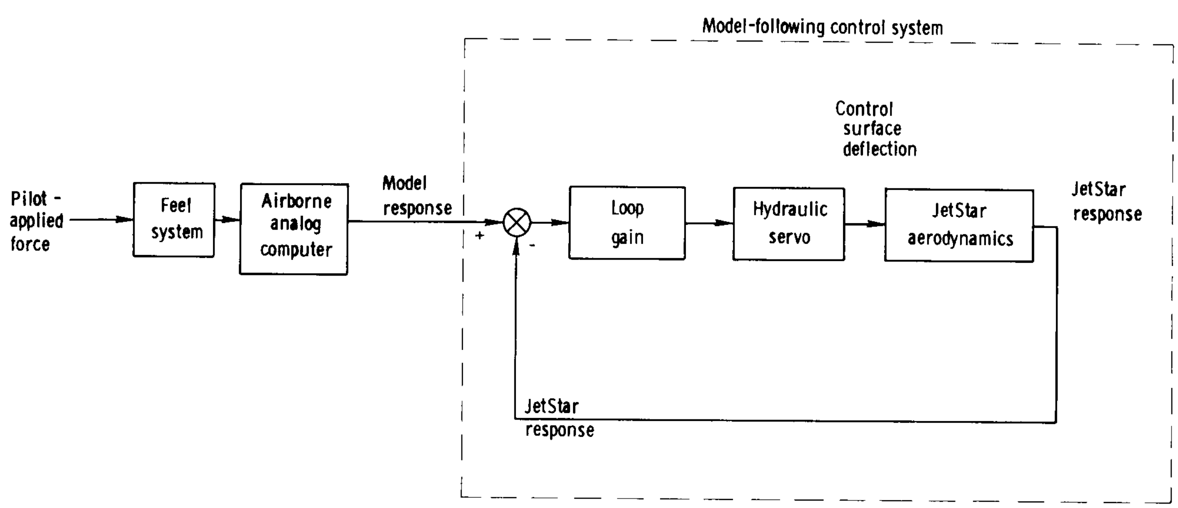


Figure 2. Simplified block diagram of GPAS model-following system.

configuration to be simulated. Selected response variables of the programed configuration (model) are fed to the model-following control system of the GPAS. Model and JetStar responses are compared, and the error signal commands a hydraulic servo through a loop gain to drive a control surface in a direction to reduce the error. With a sufficiently high loop gain, the error is small and the JetStar is forced to reproduce the dynamics of the model.

The advantages of the model-controlled system over the more conventional response feedback system, which utilizes feedback loops to augment base aircraft stability derivatives, are primarily greatly reduced in-flight calibration time and relative insensitivity to variations in base aircraft weight, inertia, and aerodynamic characteristics. The model-following system is covered later in more detail.

LATERAL AND DIRECTIONAL MOTION-CUE EFFECTS

Airborne Simulation in Perspective

The effect of the total environment on a pilot's performance in a vehicle, and on his subjective opinion, has been a subject of much discussion and study. The total environment includes all stimuli which can be sensed, either consciously or subconsciously, by the human sensory system. It is generally recognized that the pilot's response is influenced by these stimuli, but opinions vary on how much of this total environment must be duplicated realistically in any given experiment on a flight simulator. Fairly sophisticated ground simulators have been built in an attempt to realistically reproduce the flight environment. These simulators have incorporated, in various degrees, limited motion capability, color television and peripheral visual displays, and even aural cues. The development of airborne simulators has been an attempt to obtain many of the natural flight cues "free," in that an actual flight vehicle is being used. There is no doubt that a pilot of such an airborne simulator knows he is flying an airplane, but there is no experimental evidence to show that this factor alone would alter significantly the results of a handling-qualities study, for example.

The airborne simulator does have one advantage over its research companion, the ground simulator, in that it is not constrained to the confines of a laboratory. For example, an airborne simulator utilizes natural kinematic relationships instead of washout motion to provide the proper normal and lateral acceleration cues in a level turn. The true horizon can also be used as a 360° visual display. In short, many cues are automatically produced by using a real airplane. As reference 5 points out, "... the multitude of ill-defined, nonetheless important, cues which are combined by the pilot are automatically present during in-flight simulation, but these are difficult to synthesize realistically for the ground-based simulation. Furthermore, the synthesis of the pilot's cues implies that all of the important cues and their interrelationships are known and can be quantitatively specified. This is certainly a dubious assumption."

In many applications, however, the airborne simulator may not display any clear-cut dynamic advantage over a ground-base simulator. If the airborne simulator cannot be directly and independently controlled in all six degrees of freedom, compromises must be made in simulating acceleration or attitude variations. For example, in an airborne simulator lacking direct lift control, it is physically impossible to match the pilot normal-acceleration and pitch-attitude variations of some other vehicle having an arbitrary lift-force coefficient, true airspeed, and pilot location.

For a particular airborne simulator study, it would then be necessary to select those cues which are considered to be critical to the task and provide them accurately. The other cues would then be uncontrolled and, in many cases, incorrect. The selection of cues to be presented involves the same "dubious assumption" that is present in synthesizing the flight environment on the ground--the assumption that enough is known about all the interrelated effects of environment to be able to specify, a priori, what is important and what is not.

The previous discussion on compromises necessary in selecting variables to be simulated concerned a simulator which could not be independently controlled in six degrees of freedom. A six-degree-of-freedom simulator, however, is also restricted in some instances. For example, if model true airspeed is not matched, both bank angle and turn rate cannot be matched continuously in a level turn. Such a discrepancy would be large in simulating supersonic cruise with a subsonic simulator if turn rate information is to be obtained from earth reference. Thus, as is well recognized by simulator users, no simulator will ever match all the characteristics of another vehicle. A six-degree-of-freedom simulator can, however, most nearly duplicate the motion and visual cues which would be perceived in the actual vehicle. The complexity involved in providing this "total simulation" is somewhat in contrast with the aforementioned concept of obtaining the true flight environment "automatically."

Although the GPAS does not have six-degree-of-freedom control, valid research results may still be obtained. One method used in the validation program was to select those parameters for matching which were presumed to be most critical to the simulation. Experiments were then conducted to determine the sensitivity of the pilot's assessment of vehicle handling qualities to cue variations. These experiments were designed to determine if mismatched cues could have accounted for discrepancies in the GPAS which in the validation program (ref. 1) were attributed to modeling deficiencies. The specific cues in question were lateral acceleration at the pilot's location and angular motion in the roll and yaw axes.

Model-Following Considerations for the Mach 1.2 Simulation

The Mach 1.2 condition of the XB-70 airplane presented an unusual simulation problem in the GPAS. When model sideslip was matched by the GPAS on a 1:1 basis, the resulting JetStar n_{y_p} was 180° out of phase with model n_{y_p} in the frequency region around the model Dutch roll natural frequency (fig. 3). During rapid pilot aileron application, the initial JetStar n_{y_p} was in the proper direction, but, during the free oscillation, the two accelerations were nearly opposite in phase. Therefore, a pilot flying the GPAS in this condition did not obtain the same lateral acceleration (side force cues) as he would have in the XB-70 airplane for similar pilot control inputs or during a free aircraft sideslip oscillation.

The discrepancy in pilot lateral acceleration between the model and the JetStar is caused by aerodynamic and geometric differences. The expression for lateral acceleration at the pilot's location during a free oscillation is

$$n_{y_p} \approx \frac{V}{g} \left(Y_{\beta}\beta\right) + \frac{l_p}{g} \dot{r}$$

where the first term is recognized as the lateral acceleration at the center of gravity. For a model with an arbitrary true airspeed, side-force coefficient, and moment arm, l_p, it is obvious that pilot acceleration would in general not be duplicated on the JetStar. A simplified analysis shows that the two terms in the n_{y_p} equation are opposite in phase. Therefore, with a sufficiently large l_p and low Y_β, the n_{y_p} would be in phase with sideslip instead of opposite in phase as it would be for an aircraft with a shorter l_p. The l_p of the XB-70 airplane is 32 meters (105 feet), and that of the JetStar is 7 meters (23 feet). Thus for this simulation, when sideslip was matched on a 1:1 basis, the pilot lateral accelerations were out of phase in a free oscillation.

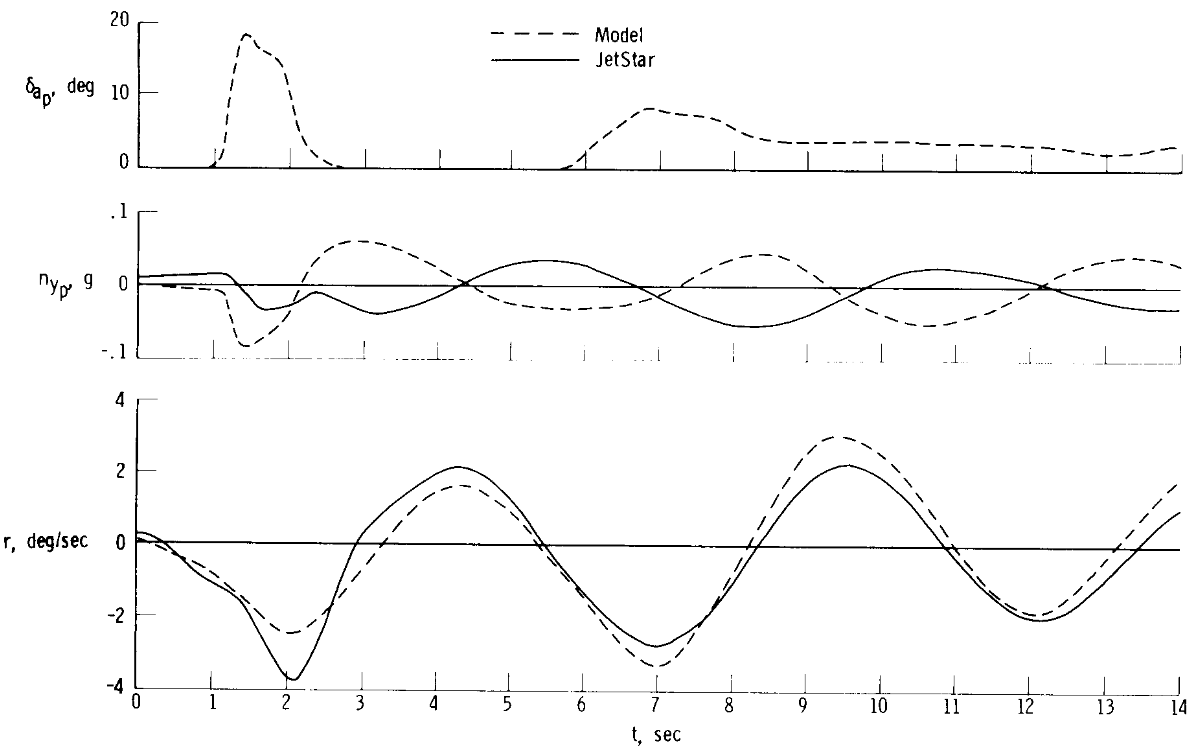


Figure 3. Model-following. XB-70 model; Mach 1.2 at 12,192 meters (40,000 feet) altitude; $\frac{\beta_J}{\beta_m} = 1.$

Figure 3 also shows that the yaw rate response of the JetStar matched the model response well, even though yaw rate was not a directly matched variable (directionally, only sideslip and sideslip rate were commands to the model-following system). For mild Dutch roll oscillations, $\dot{\beta}_m \cong -r_m$, and because β_m and $\dot{\beta}_m$ were directly matched, it is not surprising that yaw rates were similar for the model and the JetStar.

The goal for the Mach 1.2 XB-70 simulation was to determine the gross influence of lateral acceleration and yaw rate cues on pilot opinion of the configuration handling qualities. This was necessary because model n_{y_p} was not duplicated to any reasonable degree in the GPAS for the Mach 1.2 XB-70 validation flights when, according to pilot comments in reference 1, a satisfactory simulation was obtained.

Yaw rate and side force could not be controlled independently in the GPAS but could be varied together to obtain information on their effects. This was done by scaling the sideslip command to the GPAS model control system.

Ratios of JetStar sideslip to model sideslip, $\frac{\beta_J}{\beta_m}$, of -2, -1, 0, and 1 were investigated on the GPAS. In each instance, the programed model characteristics and pilot instrument display were identical; only the JetStar sideslip response was changed. Because of the dependence of r on β in the Dutch roll, the JetStar yaw rate was affected as well. The JetStar always turned in the correct direction, however, because $\beta \cong 0°$ for a steady turn and the sideslip scaling or reversal had no effect. Model-following for $\frac{\beta_J}{\beta_m} = -1$ is shown in figure 4. The sideslip response is not shown, but JetStar sideslip was nearly 180° out of phase with the model sideslip. JetStar roll rate following was independent of sideslip scaling. JetStar n_{y_p} initially responded in the wrong direction when rapid inputs were applied, but duplicated model n_{y_p} during the free oscillation.

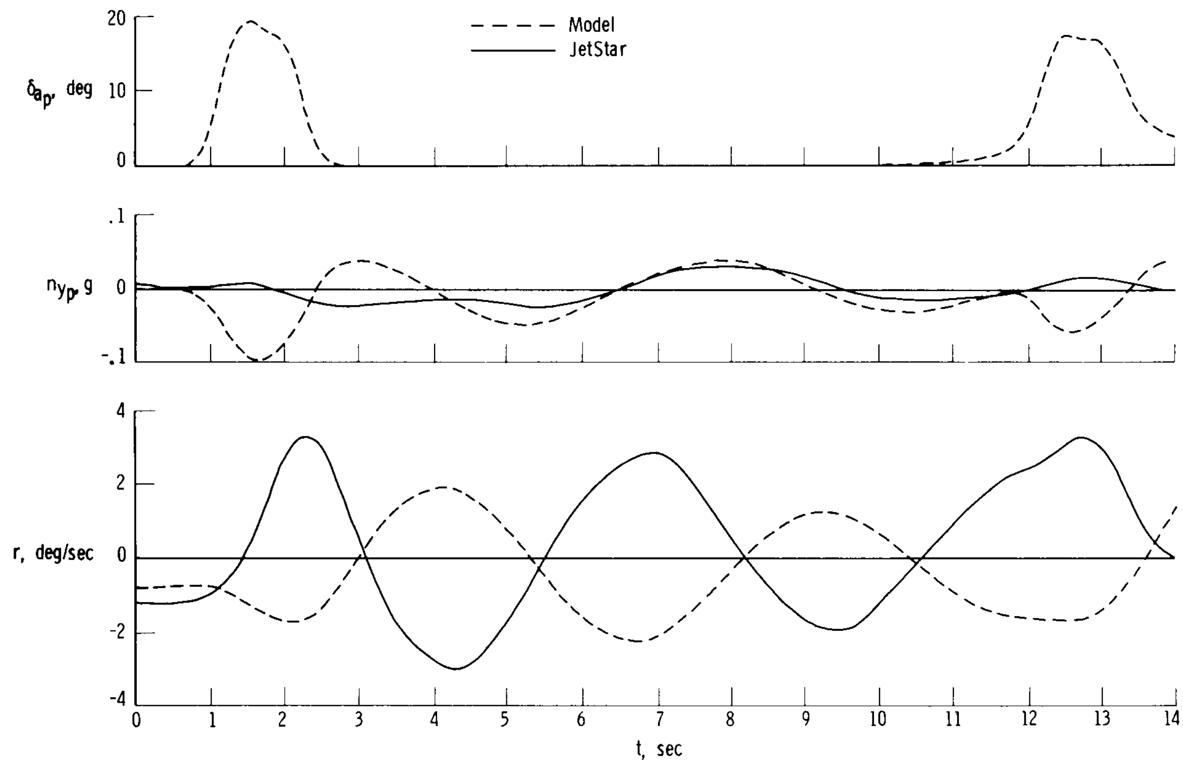


Figure 4. Model-following. XB-70 model; Mach 1.2 at 12,192 meters (40,000 feet) altitude; $\frac{\beta_J}{\beta_m} = -1$.

Thus, when $\frac{\beta_J}{\beta_m} = 1$, yawing angular velocity, rolling angular velocity, and sideslip itself were matched well, with JetStar n_{y_p} grossly correct for sharp pilot inputs and reversed in phase during a free oscillation. For $\frac{\beta_J}{\beta_m} = -1$, yawing angular velocity and sideslip were reversed, rolling angular motions were correct, and JetStar n_{y_p} was reversed initially for sharp aileron inputs and correct for a free oscillation.

A ratio of $\frac{\beta_J}{\beta_m} = -2$ yielded larger JetStar motions with the same phase relationships described for the ratio of -1. An example is shown in figure 5. The initial reversal in

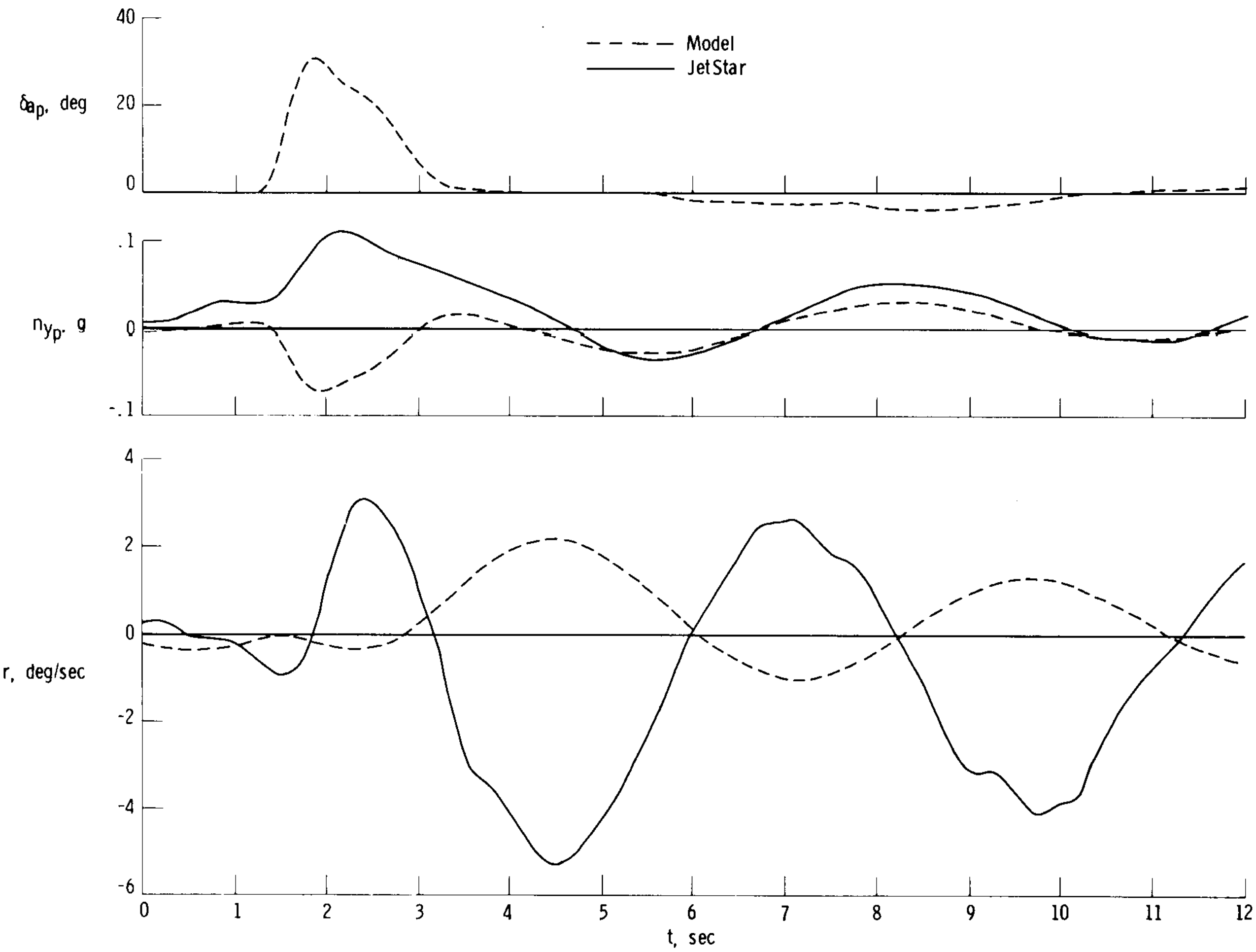


Figure 5. Model-following. XB-70 model; Mach 1.2 at 12,192 meters (40,000 feet) altitude; $\frac{\beta_J}{\beta_m} = -2$.

JetStar n_{y_p} was more pronounced and its magnitude was slightly larger than that of the model during the free oscillation portion of the response. The ratio of $\frac{\beta_J}{\beta_m} = 0$ shown in figure 6 was interesting because JetStar sideslip was constrained to zero during all maneuvering. This resulted in near-zero lateral acceleration at all times and reduced yaw motion during Dutch roll oscillations. Consequently, the pilot observed Dutch roll responses on his sideslip indicator, but felt very little directional motion.

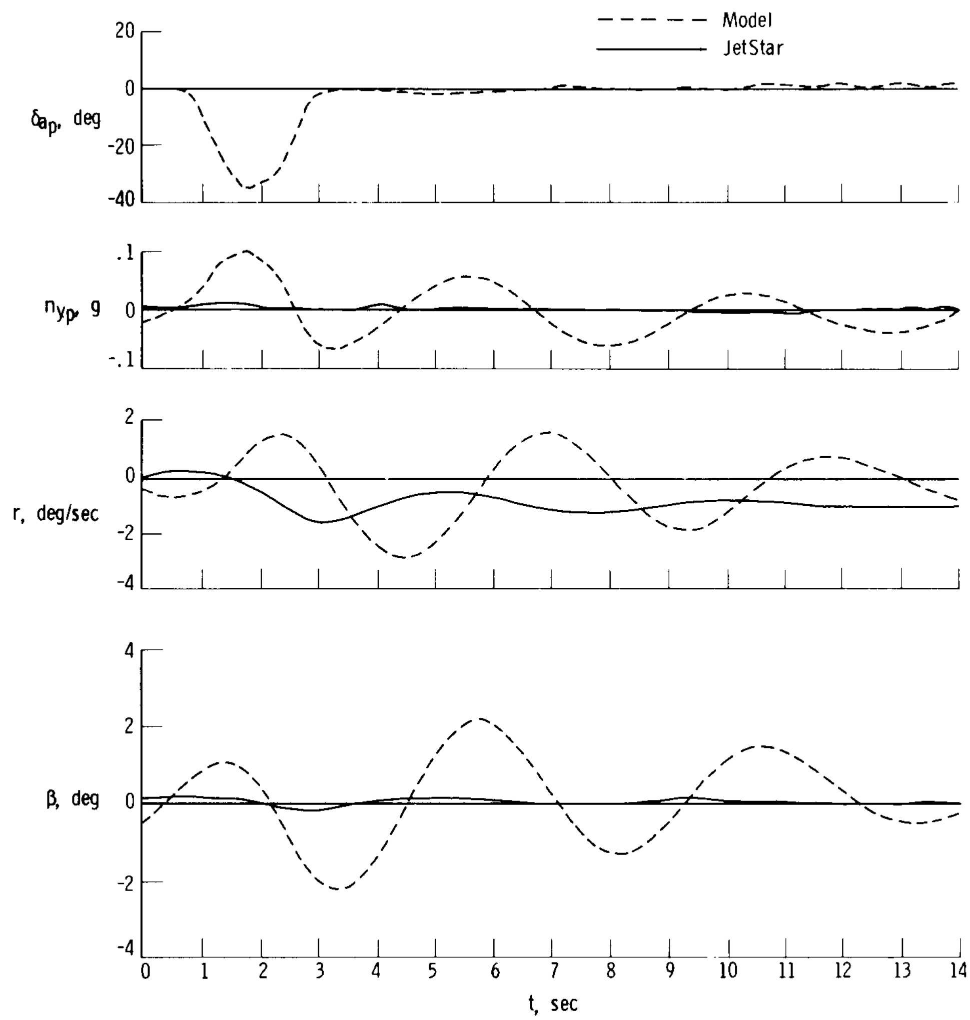


Figure 6. Model-following. XB-70 model; Mach 1.2 at 12,192 meters (40,000 feet) altitude; $\frac{\beta_J}{\beta_m} = 0$.

Table 1 summarizes measured characteristics for each of the $\frac{\beta_J}{\beta_m}$ ratios presented to the evaluation pilot.

TABLE 1.—SUMMARY OF DIRECTIONAL MOTION FOLLOWING FOR XB-70 MODEL AT MACH 1.2 AND 12,192 METERS (40,000 FEET) ALTITUDE

Selected ratio, $\frac{\beta_J}{\beta_m}$	Resultant ratio, $\left(\frac{n_{y_{p_J}}}{n_{y_{p_m}}}\right)_{\text{Dutch roll}}$	Resultant ratio, $\left(\frac{r_J}{r_m}\right)_{\text{Dutch roll}}$
-2	1.5	-2.6
-1	.6	-1.3
0	0	-.2
1	-.6	1.3

Pilot Evaluations of Scaled Sideslip Cases for the Mach 1.2 Simulation

Several pilots evaluated the scaled sideslip cases, which were intermixed with configurations being evaluated for another GPAS study involving XB-70 lateral-directional handling qualities. Flight plans instructed pilots to comment on roll power, roll damping, Dutch roll damping, adverse yaw due to aileron, and the level of side force. Tasks included slow and fast turns to selected headings, aileron rolls, and aileron pulses. Pilots assigned handling-qualities ratings using the Cooper-Harper scale (ref. 6). Figure 7 is a summary of results obtained for the XB-70 aerodynamic model that had been judged to be representative of the XB-70 airplane (ref. 1). During the validation program described in reference 1, only $\frac{\beta_J}{\beta_m} = 1$ was used. All the evaluations were made under visual flight rules. In figure 7 brief pilot comments are included with the ratings. The figure shows results for only one pilot but is a valid representation of the collective results. Pilot comments and ratings led to the following observations:

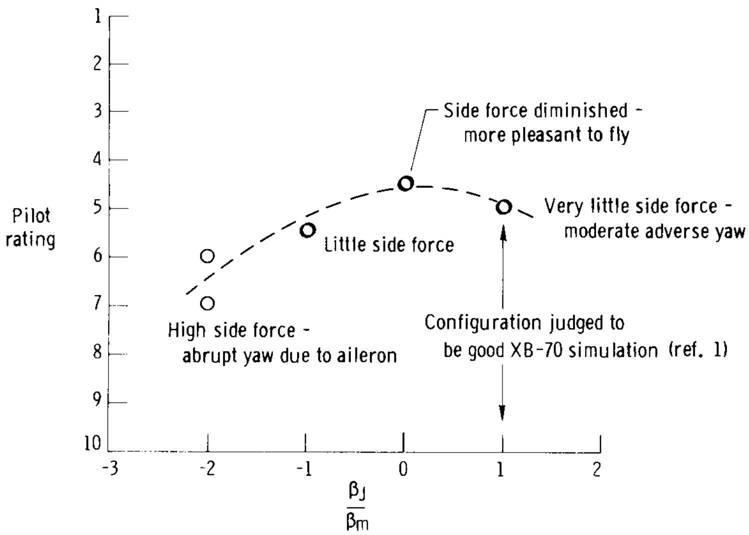


Figure 7. Sensitivity of one pilot to directional motion cues. XB-70 model at Mach 1.2; instrument display driven from computer model.

(1) The $\frac{\beta_J}{\beta_m} = 0$ configuration was always rated slightly better than other sideslip-following ratios. This condition was somewhat more pleasant to fly than the $\frac{\beta_J}{\beta_m} = 1$ condition because of reduced "side force." (The pilots did not distinguish between angular and linear rates and accelerations.) Some pilots considered the Dutch roll damping of this condition to be slightly better and some thought the adverse yaw due to aileron was slightly less. They all agreed, however, that the condition warranted an improved rating, usually an increment of 1/2 to 1 rating, when compared with the $\frac{\beta_J}{\beta_m} = 1$ configuration.

(2) Little difference was noted in the $\frac{\beta_J}{\beta_m} = 1$ and -1 conditions. The comments associated with these two conditions were usually identical, which indicates that there was no inherent association of phasing (±) of directional cues with the Dutch roll response by the pilots for this condition. Thus, phasing of directional motion cues in the Dutch roll oscillation was not critical in the representation of XB-70 flying qualities for the Mach 1.2 condition.

(3) The $\frac{\beta_J}{\beta_m} = -2$ condition was always given the poorest rating, and the most common complaint was the abrupt adverse yaw or abrupt "side force." In some instances, the pilots thought that adverse yaw had actually been increased; in others they observed that they were feeling more side force but not getting much more adverse yaw (as indicated on the model-driven sideslip instrument) due to aileron. The abrupt initial response is evident in figure 5 in both the lateral acceleration and yaw rate responses of the JetStar.

(4) Although there is little or no directional motion in the $\frac{\beta_J}{\beta_m} = 0$ condition, the pilots noted only a slight change in overall flying qualities. This further suggested that a fixed-base simulator would have satisfactorily represented the XB-70 airplane at this flight condition.

The GPAS was operated in a fixed-base manner while airborne, so that the fixed-base and in-flight moving-base simulations of the XB-70 airplane could be compared at $\frac{\beta_J}{\beta_m} = 0$. The pilot flew the analog model alone, by reference to instruments, without engaging the variable-stability system. This mode of operation was identical to GPAS ground operation in which no external visual display was available. In flight the pilot wore a hood while evaluating the nonmoving configuration, in order to eliminate any possible visual cues. By engaging or disengaging the variable-stability system, he was able to make detailed comparisons between the two simulation presentations. It should be noted that the visual display was also a variable, in that the evaluation pilot lifted his hood for the moving-base simulation. These two conditions represented extremes in simulation. The following excerpts from one pilot's comments describe the comparison:

"With aircraft motion and the outside horizon visible, the roll power seems adequate, although it's not very high. At this speed in the XB-70 you do not normally use much aileron, and, if you do, you get 1° to 2° of sideslip. The roll response is adequate.

"When flying the nonmoving configuration, I have the feeling I can put in slightly more lateral control. With that amount of aileron the attitude indicator does not show a very rapid bank-angle change, and I have the feeling that I don't have enough roll power. However, with full aircraft motion I do not feel like I want very much--there is a difference in the viewpoint of the pilot.

"Also, with airplane motion, I feel that 1 1/2° to 2° of sideslip is too much. When flying the nonmoving configuration, I know I do not want to generate a lot of sideslip, but 1 1/2° to 2° on the sideslip indicator doesn't impress me as much as it does with aircraft motion present.

"I rate the lateral-directional characteristics as a 4 with airplane motion and 4 1/2 without motion because of the apparent roll power difference."

The apparent difference in roll power between the two conditions prompted the evaluation of one other configuration, that of instrument flight with full GPAS motion. The pilot who made the preceding comments considered the roll power of this condition to be more like that in the VFR situation than that in the nonmoving condition, but still thought roll power was higher when he had the actual horizon in view. It appears, then, that both rolling motion and the visual scene affected the pilot's opinion of apparent roll power.

The results of the cues experiments led to the following observations concerning the validation results of the Mach 1.2 simulation:

(1) The relative insensitivity of the pilot to fairly large variations in directional motion cues suggested that the mismatch in n_{y_p}, in light of the considerably stronger match in yaw angular motion, did not significantly affect pilot opinion of the condition.

(2) Discrepancies noted by one pilot in the XB-70 simulation on GPAS flight 45 (ref. 1) were assumed to be caused by an inadequate description of the XB-70 airplane on the programed model. As a result, model characteristics were modified to yield an acceptable simulation on that flight, based on pilot opinion. Examination of pilot comments and ratings given during the cues experiments showed that slight cue variations, on the order of the mismatch in n_{y_p}, would not have corrected the deficiencies noted by the pilot on GPAS flight 45 (ref. 1).

(3) If the airborne analog computer were programed to represent the XB-70 airplane at Mach = 1.2 and an altitude of 12,192 meters (40,000 feet), the GPAS would provide an accurate and realistic simulation when sideslip and bank angle were matched.

Motion-Cue Experiments for the Mach 2.35 Simulation

The XB-70 airplane at the Mach 2.35 flight condition, as described in reference 1, exhibited a moderate PIO tendency in the lateral-directional mode. It was necessary to determine the role that motion and visual display fidelity played in the realistic simulation of this condition. This was done by using the same model aerodynamic representation with various combinations of motion and visual displays.

Before discussing the results of these cues experiments, it is of interest to examine GPAS motion simulation fidelity for the XB-70 model. Figure 8 shows n_{y_p}, p, and r responses of the JetStar for a model double aileron pulse. The n_{y_p} response during the aileron input is in the correct direction. During the free oscillation, JetStar n_{y_p} leads the model n_{y_p} response by approximately 90°. (The acceleration-following for this model is shown to be a highly sensitive function of frequency in a later section of this report.) Both roll rate and yaw rate are duplicated fairly well.

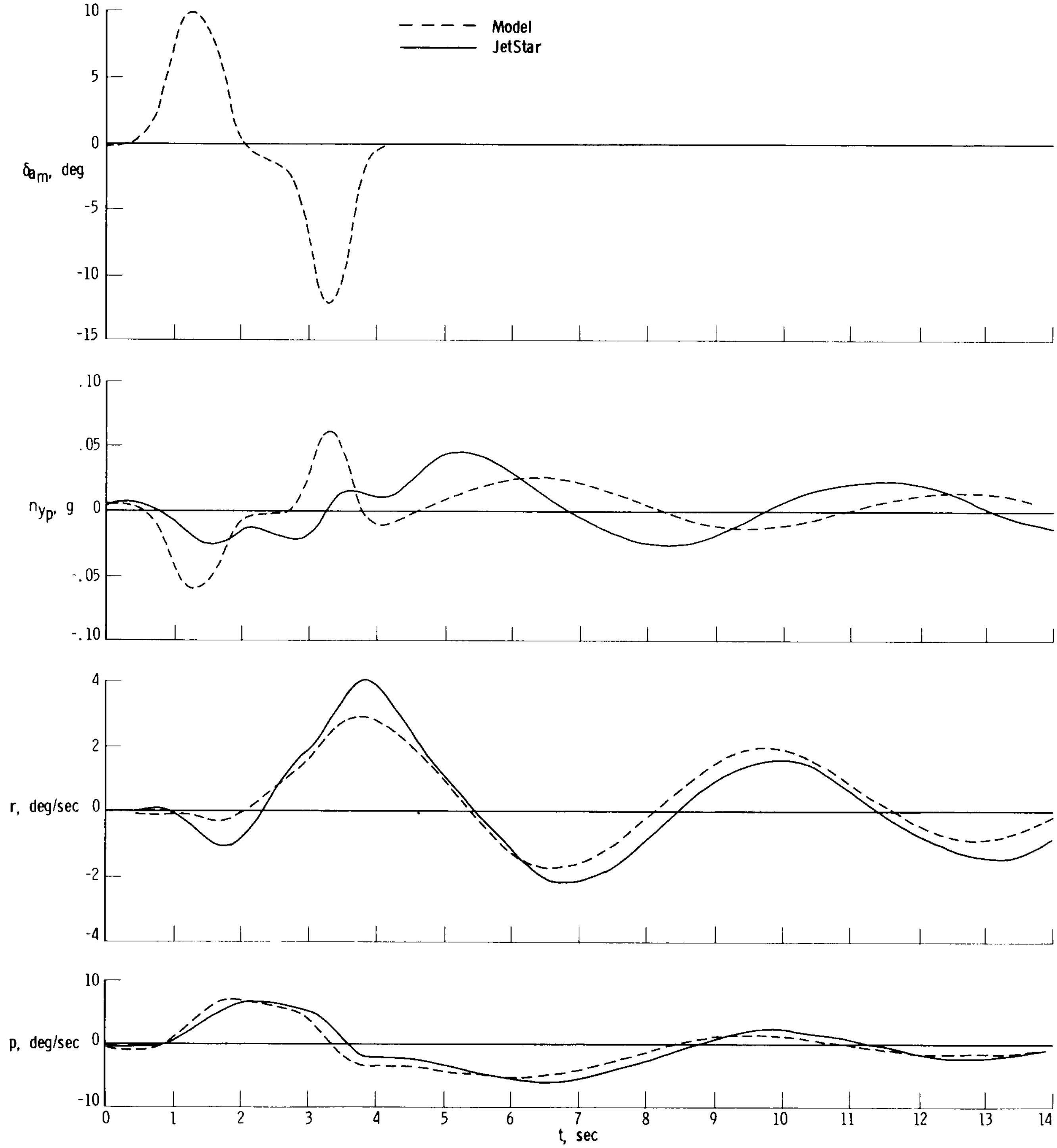


Figure 8. Duplication of motion cues on GPAS. XB-70 model; Mach 2.35.

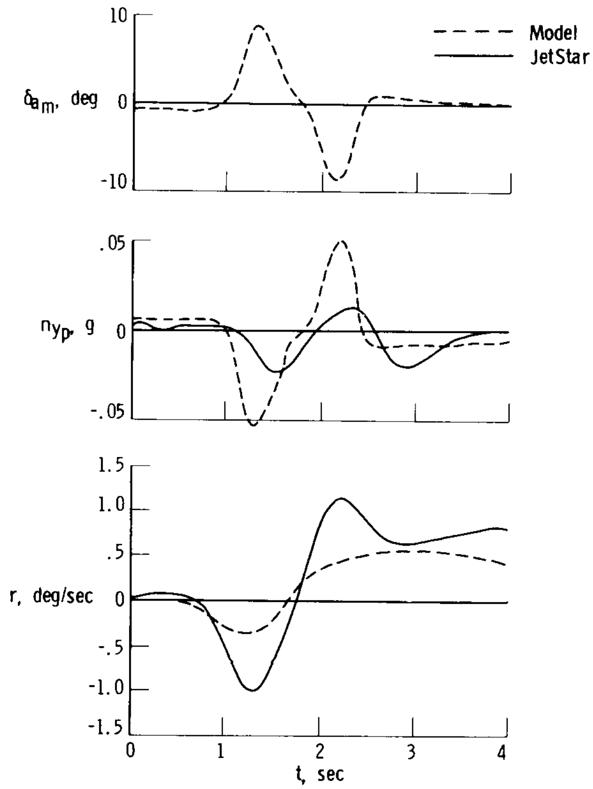


Figure 9. Directional motion reproduction fidelity on GPAS. XB-70 model; Mach 2.35.

Another double aileron pulse is shown in figure 9. The pulses are accomplished in a shorter time interval, resulting in a higher input frequency content than that presented in figure 8. The JetStar lateral acceleration and yaw rate responses now differ considerably from those of the model. Model-following frequency-response data presented later show yaw rate and especially lateral-acceleration matching to be sensitive to frequency.

A further comparison of JetStar and XB-70 responses was made by using a technique described in reference 1. The pilot's wheel position was recorded during an XB-70 aileron maneuver. This signal was introduced into the GPAS airborne computer as a pilot command. The JetStar response could then be compared directly with the actual XB-70 response because the pilot input was identical. Figure 10 shows a fair duplication of XB-70 n_{y_p} and yaw rate, especially during the forced oscillation portion of the maneuver.

The following conclusions are drawn from figures 8 to 10 concerning motion simulation on the GPAS for the Mach 2.35 XB-70 model:

(1) Roll-rate following was good for all normally encountered XB-70 types of roll maneuvers performed on the GPAS.

(2) JetStar n_{y_p} and r response to sharp model aileron inputs were generally in the correct direction, but they were not of the proper magnitude.

(3) Model-following for n_{y_p} and r was highly sensitive to frequency, but, during a driven oscillation, JetStar pilot lateral acceleration and yaw rate closely resembled actual XB-70 response (fig. 10).

The motion-cue experiments chosen for this XB-70 model were slightly different from those for the Mach 1.2 XB-70 model. GPAS system difficulties prevented an entire series of scaled sideslip conditions from being evaluated. Only the $\frac{\beta_J}{\beta_m} = 1$ and 0 conditions could be evaluated. The cases evaluated were as follows:

Visual display	Motion
Instruments only	None
Instruments only	$\frac{\beta_J}{\beta_m} = 0$
Instruments only	$\frac{\beta_J}{\beta_m} = 1$
Instruments + horizon (VFR)	$\frac{\beta_J}{\beta_m} = 0$
Instruments + horizon (VFR)	$\frac{\beta_J}{\beta_m} = 1$

The pilot was instructed to evaluate each condition in terms of its lateral-directional

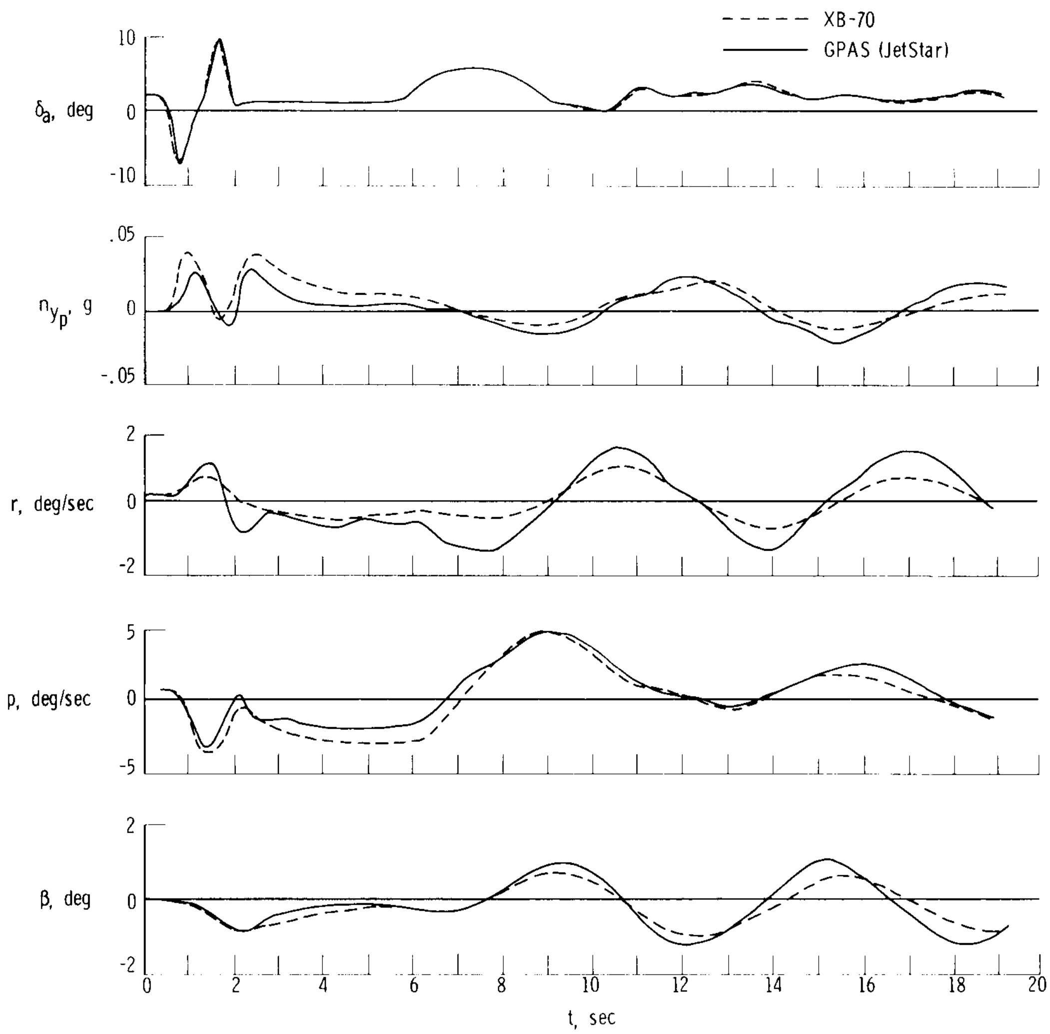


Figure 10. Comparison of GPAS response with best XB-70 model and actual XB-70 aircraft at Mach 2.35.

handling qualities and to comment on adverse yaw due to aileron, roll power, and PIO tendency. The pilot was not given the conditions in the order shown, but was given pairs of conditions to evaluate, one of which was usually the VFR, full motion case.

Pilot comments and ratings on this series of runs are presented in the appendix. The major comments were as follows:

(1) A fixed-base simulation with a standard aircraft attitude indicator would not provide an adequate simulation of this XB-70 condition, either from the pilot's point of view or for the researchers, because the PIO tendency is suppressed and the pilot rating is changed significantly.

(2) Successive addition of motion and visual cues to a fixed-base simulation, with instrument display alone, worsened the PIO situation and the pilot rating.

(3) With the instrument display alone, successive addition of the roll and yaw degrees-of-freedom motion worsened the PIO situation, indicating a motion effect independent of visual cues. Figure 11 summarizes this condition. Several motion cue

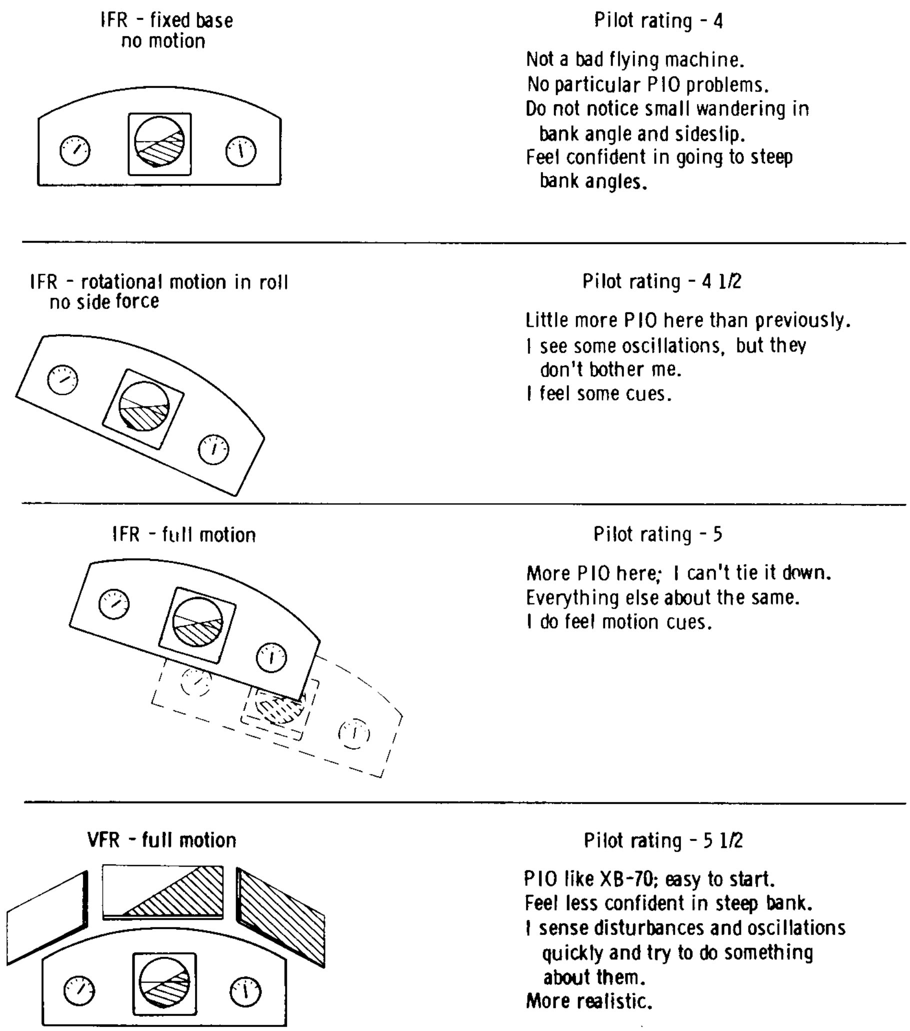


Figure 11. Summary of cues results for the XB-70 Mach 2.35 simulation.

experiments performed on moving-base simulators have shown that marginally stable configurations usually appear worse when cockpit motions are absent. The GPAS experiments show the opposite trend for the particular set of aircraft dynamics simulated $\left(\frac{\omega_\varphi}{\omega_\psi} > 1.0\right)$. The pilot detected aircraft disturbances more quickly with motion or with the actual horizon and tended to correct for them, leading to a pilot-induced oscillation. The reason for increased pilot gain in the lateral control loop without the additional lead needed to maintain adequate phase margin is not known.

Thus the Mach 2.35 XB-70 model handling qualities appear to be fairly sensitive to motion and visual cue presentations. Therefore a high quality motion simulation would be required to represent the Mach 2.35 XB-70 handling qualities satisfactorily. One discrepancy noted in reference 1 was in Dutch roll damping ratio; the pilot required a lower value in the GPAS ($\zeta = 0.094$) primarily to improve the GPAS simulation of the XB-70 PIO tendency ($\zeta = 0.133$). The possibility remains that this lower model damping ratio was required to compensate for the mismatch in the lateral acceleration or visual presentation to the pilot in the GPAS.

Additional Remarks on Cues Experiment

The cues experiments performed on the GPAS were limited by several factors. The most critical was the inability to hold all parameters reasonably constant, except the one being studied. Without independent control over all degrees of freedom, the GPAS could not be used in an ideal manner. However, scaled sideslip or yaw-rate following, as well as in-flight comparisons of fixed versus moving-base simulation, are techniques which may be used to ascertain the gross influence of motion and visual cues on pilot control of specific configurations. This type of information is not really required at this time, because several simulator studies have shown the existence of motion and visual cue effects. The need is for carefully controlled experiments which lead to a more complete understanding of the individual, often subtle, effects of angular rate and acceleration, linear acceleration, and type and size of the display. Detailed knowledge of these individual effects on pilot opinion and performance is necessary to accurately predict, for example, simulator requirements for a certain level of simulation fidelity.

The GPAS validation program showed that an aircraft (XB-70) with characteristics significantly different from those of the JetStar could be represented realistically without duplicating all the motions exactly. It was possible to demonstrate this because the pilot could make comparisons with the actual vehicle. In many cases such direct comparisons will not be possible, for example, if the model represents an aircraft not yet built, or even if the model configuration representing an existing aircraft is altered significantly to reflect proposed stability augmentation schemes or aerodynamic changes. In such instances tests must be made frequently to detect contamination of results caused by cue mismatches. These tests would check for pilot sensitivity to the questionable cue. If pilot sensitivity were low, the mismatch most likely could be neglected. If it were high, the cue would either have to be duplicated more faithfully or its effect understood thoroughly enough to enable results obtained with improper cues to be corrected.

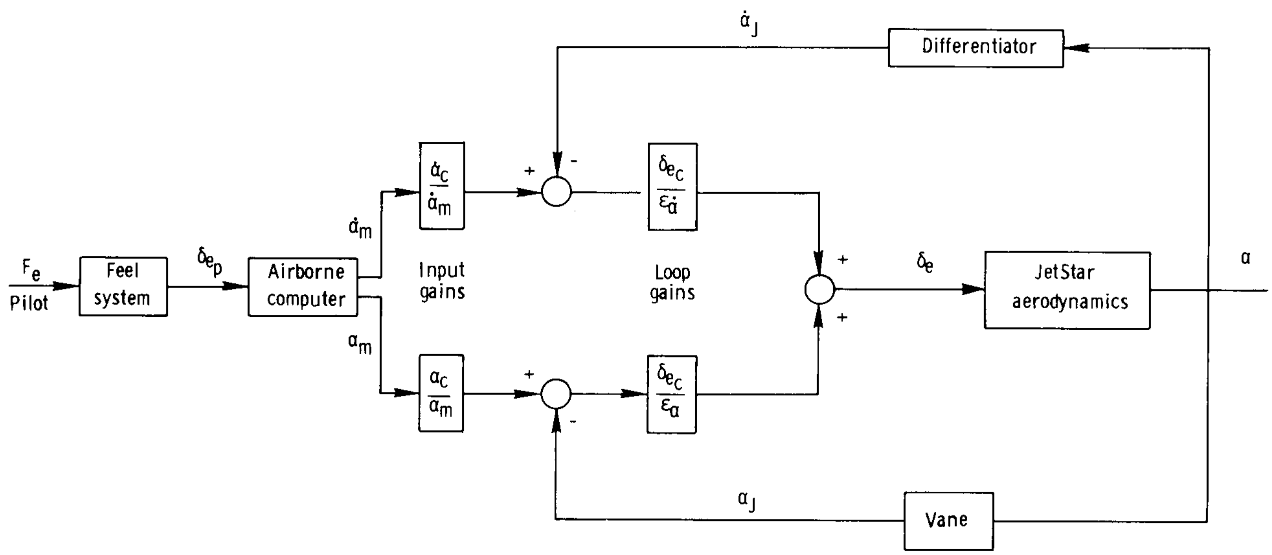
Thus the GPAS validation result shows that it would be presumptuous to assume that the use of an airborne simulator would be automatically better than the use of a ground simulator if six-degree-of-freedom capability is not provided. The six-degree-of-freedom airborne simulator does hold the promise of automatic flight environment duplication. It appears that the precise duplication of all dynamic cues with such a six-degree-of-freedom airborne simulator may be easier to accomplish than the determination of the effects of mismatched cues with a limited motion simulator.

MODEL-FOLLOWING EXPERIENCE

The GPAS validation program was conducted by using the model-controlled system as the means of simulating the desired dynamic characteristics. Because the assumptions and compromises made in the validation program depend largely on the limitations and capabilities of the MCS, it is worthwhile to review the flight experience with the MCS and to describe methods which are useful in verifying that certain response variables are followed satisfactorily.

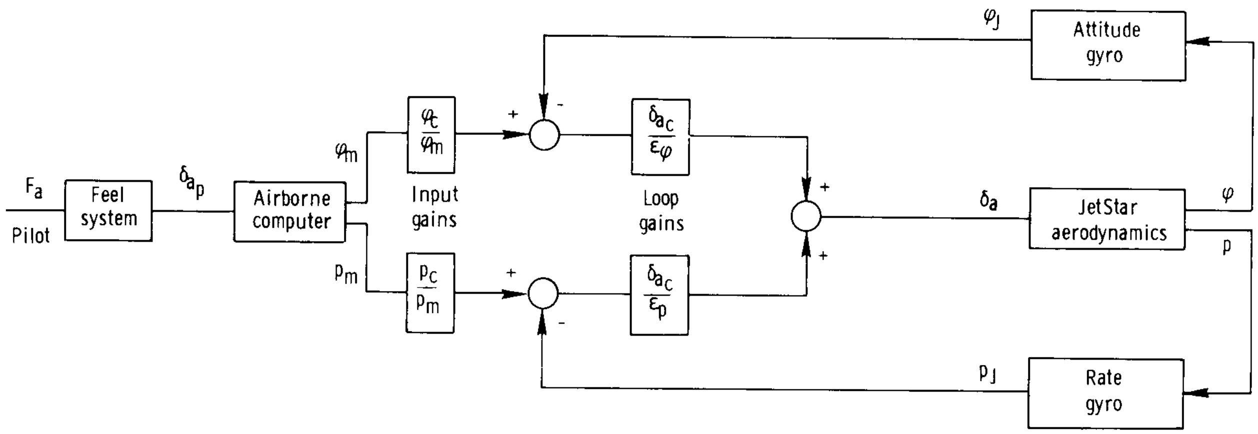
Selection of Variables To Match and Associated Gain Values

Only the three conventional JetStar control surfaces were used to match model responses; therefore, it was not possible to duplicate the six-degree-of-freedom motions of the programed vehicle. It was decided to match α and $\dot{\alpha}$ in the longitudinal mode and β, $\dot{\beta}$, φ, and p in the lateral-directional mode. The decision to match α and β rather than n_{z_p} and n_{y_p} was made because the acceleration-following loops had not been checked out. The model-following configuration used in the GPAS validation program is shown in figures 12(a) to 12(c). The loop gains and input gains used are

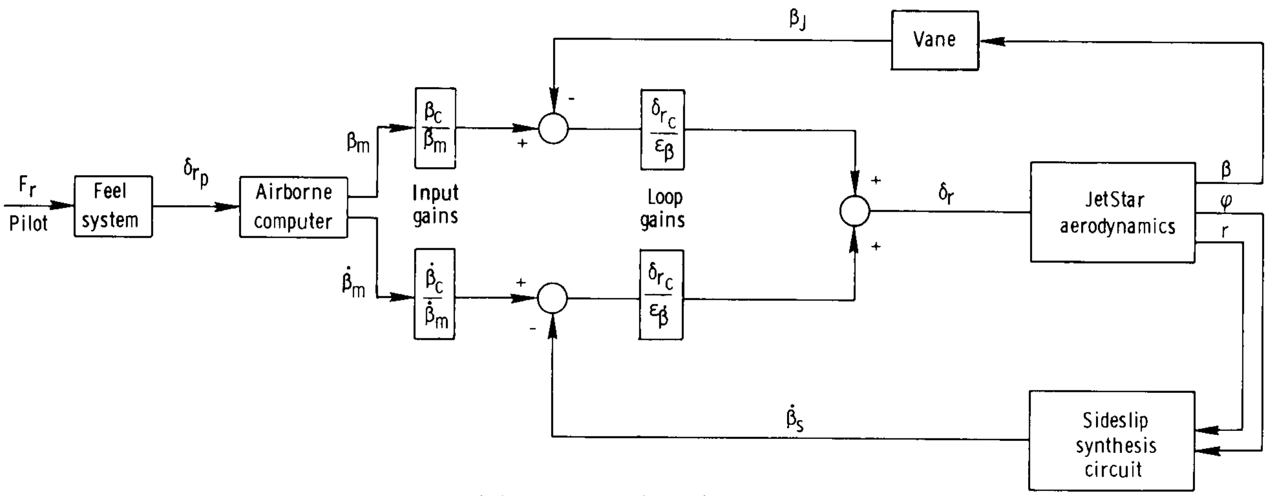


(a) Longitudinal configuration.

Figure 12. Block diagram of two-loop configuration of model-controlled system used during GPAS validation program.



(b) Lateral configuration.



(c) Directional configuration.

Figure 12. Concluded.

presented in table 2. The loop gains, $\frac{\delta_{e_c}}{\epsilon_\alpha}$ and $\frac{\delta_{r_c}}{\epsilon_\beta}$, which primarily affect GPAS closed-loop frequency (or bandwidth) were selected to be as large as possible, constrained by system noise and the ability to obtain an adequate amount of closed-loop damping. Both gains reduced GPAS closed-loop damping as they increased longitudinal short-period and Dutch roll natural frequencies, respectively. For the longitudinal mode, $\frac{\delta_{e_c}}{\epsilon_{\dot{\alpha}}}$ was used as the damping loop, and a gain of -0.3 was judged to be the highest value that could be used to yield an acceptable level of noise in the elevator servo channel.

The vane angle-of-attack signal was differentiated and filtered to produce $\dot{\alpha}$, but the signal was still noisy. With a maximum usable gain of $\frac{\delta_{e_c}}{\epsilon_{\dot{\alpha}}} = -0.3$, $\frac{\delta_{e_c}}{\epsilon_\alpha}$ was increased until closed-loop damping had diminished to the lowest desirable value

TABLE 2. – MODEL-CONTROLLED-SYSTEM GAINS USED DURING GPAS VALIDATION PROGRAM

Input gain	Value
$\frac{\alpha_c}{\alpha_m}$	1.80
$\frac{\dot{\alpha}_c}{\dot{\alpha}_m}$	1.80
$\frac{\varphi_c}{\varphi_m}$	1.00
$\frac{p_c}{p_m}$	1.00
$\frac{\beta_c}{\beta_m}$	1.80
$\frac{\dot{\beta}_c}{\dot{\beta}_m}$	.60

Loop gain	Value
$\frac{\delta_{e_c}}{\epsilon_\alpha}$ deg/deg	[a]-1.20
$\frac{\delta_{e_c}}{\epsilon_{\dot{\alpha}}}$ deg/deg/sec	[a]-.30
$\frac{\delta_{a_c}}{\epsilon_\varphi}$ deg/deg	2.50
$\frac{\delta_{a_c}}{\epsilon_p}$ deg/deg/sec	1.00
$\frac{\delta_{r_c}}{\epsilon_\beta}$ deg/deg	[a]-10.00
$\frac{\delta_{r_c}}{\epsilon_{\dot{\beta}}}$ deg/deg/sec	-2.00

[a]Gains corrected for vane position error.

(ζ_{sp} = 0.3 to 0.4). This resulted in a closed-loop GPAS short-period frequency of 4.48 rad/sec.

It is desirable that the ratio of the bandwidth of the closed-loop GPAS to the input signal bandwidth be as large as possible. The inputs are only model responses, however, and input signal bandwidth can be thought of as being closely related to natural frequencies of the modes represented in the model. The short-period frequencies of the XB-70 airplane at Mach 1.2 and 2.35 were 2.0 rad/sec and 1.51 rad/sec, respectively. The ratio of GPAS closed-loop frequency to model short-period frequency (closely related to the common -3 dB bandwidth definition) was 2.24 for the Mach 1.2 simulation and 3.0 for the Mach 2.35 simulation. It is not possible to specify the bandwidth ratio necessary for adequate model-following accuracy because model-following fidelity is generally a strong function of frequency, as is shown in the next section. Also, bandwidth ratio alone is insufficient to describe fidelity over the entire frequency range of interest. No other model-following loops were used longitudinally. The initial velocity and altitude of the JetStar were determined by the pre-engagement trim condition and were uncontrolled during the evaluations.

In the lateral-directional mode, $\frac{\delta_{r_c}}{\epsilon_\beta}$ and $\frac{\delta_{r_c}}{\epsilon_{\dot{\beta}_s}}$ were used to provide the proper directional mode, with adequate closed-loop Dutch roll damping provided by $\frac{\delta_{r_c}}{\epsilon_{\dot{\beta}_s}}$ by using the following simplified side-force equation (ref. 7):

$$\dot{\beta}_s \approx \frac{g}{V} \sin \varphi - r$$

The component signal noise levels are low, because both φ and r are obtained from gyros. The resulting $\dot{\beta}_s$ signal is also low in noise level, allowing high $\frac{\delta_{r_c}}{\epsilon_{\dot{\beta}_s}}$ gains. The limiting factor in the GPAS directional-mode frequency response was noise associated with the β signal. A gain of $\frac{\delta_{r_c}}{\epsilon_\beta} = -10$ was sufficiently high to provide a high bandwidth ratio of GPAS to XB-70 model, yet low enough to keep noise in the rudder servo channel at an acceptable level. Bandwidth ratios (Dutch roll frequencies) for the GPAS and XB-70 airplane for directional motions were 3.57 for the Mach 1.2 simulation and 4.58 for the Mach 2.35 simulation. Values of gain for the roll-following loops, $\frac{\delta_{a_c}}{\epsilon_\varphi}$ and $\frac{\delta_{a_c}}{\epsilon_p}$, were chosen to provide good roll-rate following as well as high quality bank-angle matching. The gain values in table 2 yielded acceptable performance in the roll-following axis but were not the result of any extensive analysis. Table 3 compares open- and closed-loop JetStar dynamics. The actual GPAS closed-loop roll response appeared on flight records to be either a highly damped second-order or a double-root first-order response. The exact form of the response was difficult to determine because system nonlinearities obscured the response when aileron deflections were small. Digital calculations predicted that the roll-spiral dynamics would be second order, as shown in table 3, with $\omega = 2.2$ rad/sec and $\zeta = 0.77$.

TABLE 3.—COMPARISON OF GPAS OPEN-LOOP DYNAMICS WITH JETSTAR CLOSED-LOOP CHARACTERISTICS

[JetStar at Mach 0.55 and 6096 m (20,000 ft) altitude; weight = 12,700 kg (28,000 lb)]

Parameter	Open-loop JetStar	Closed-loop GPAS
ω_{sp}, rad/sec	2.58	4.48
ζ_{sp}	0.36	0.40
ω_ψ, rad/sec	1.75	4.60
ζ_ψ	.12	.30
τ_r, sec	.36	Roots computed to be complex, $\omega = 2.2$ rad/sec, $\zeta = 0.77$
τ_s, sec	86.0	

The values for input gains (table 2) were selected to provide nearly 1:1 amplitude-following along with small phase errors for the range of expected input signal frequency content. This range centered around model natural frequencies for each mode represented.

The $\dot{\alpha}$, $\dot{\beta}_s$, and p feedbacks are, in effect, stabilization loops, as mentioned previously. Their purpose was to provide good GPAS closed-loop damping for their respective modes. As noted in figure 12, the rate variable was model-followed as well. In the longitudinal mode an error signal was developed between $\dot{\alpha}_m$ and $\dot{\alpha}_J$. By following these rate terms, some effective lead was introduced into the model-following channels. Thus, input gains can be thought of as terms in an input filter, with $\frac{\alpha_c}{\alpha_m}$ closely associated with the static gain of the filter, and $\frac{\dot{\alpha}_c}{\dot{\alpha}_m}$ with the lead term time constant. In practice, the two input gains did not exert independent control over amplitude and phase of α-following and, as such, had to be adjusted iteratively.

To select input gain values the model was driven at its natural frequency and $\frac{\alpha_c}{\alpha_m}$ and $\frac{\dot{\alpha}_c}{\dot{\alpha}_m}$ were adjusted in an iterative manner until α_J and α_m oscillated at the same amplitude with a minimum phase difference. (The same procedure was used in the lateral-directional model to select sideslip and roll input gains.) This procedure was carried out during ground simulations and checked during flight. Ground-obtained values were found to be sufficiently accurate, so further in-flight adjustments were minimal.

Frequency-Response Tests of Lateral-Directional Model-Following Performance

Model-following fidelity can be assessed in several ways. The actual time histories of model and JetStar responses can be compared, as in reference 1. This method yields information about model-following during the particular maneuver being analyzed. Frequency responses of the entire model-following system yield information in the frequency domain which can also be applied to the time domain. Ground and flight tests of model-following performance were conducted on the GPAS in an attempt to describe more clearly system performance observed during the validation program.

Figure 13 is a block diagram of the test setup. An oscillator was used to apply sinusoidal δ_{a_m} inputs to the airborne computer with the GPAS in the model-following mode. For the ground tests, the JetStar aerodynamic characteristics were represented by a set of six-degree-of-freedom equations programed on an analog computer external to the JetStar. The JetStar control system was operated as in flight with actual control-surface deflections used as the input to the ground analog computer. Of interest is the comparison of ground and flight results, because this is indicative of the accuracy of the analog representation of the JetStar. Also, these tests showed the validity of using the ground simulation for experimental work in model-following or for the setup of the model-following system for airborne simulation.

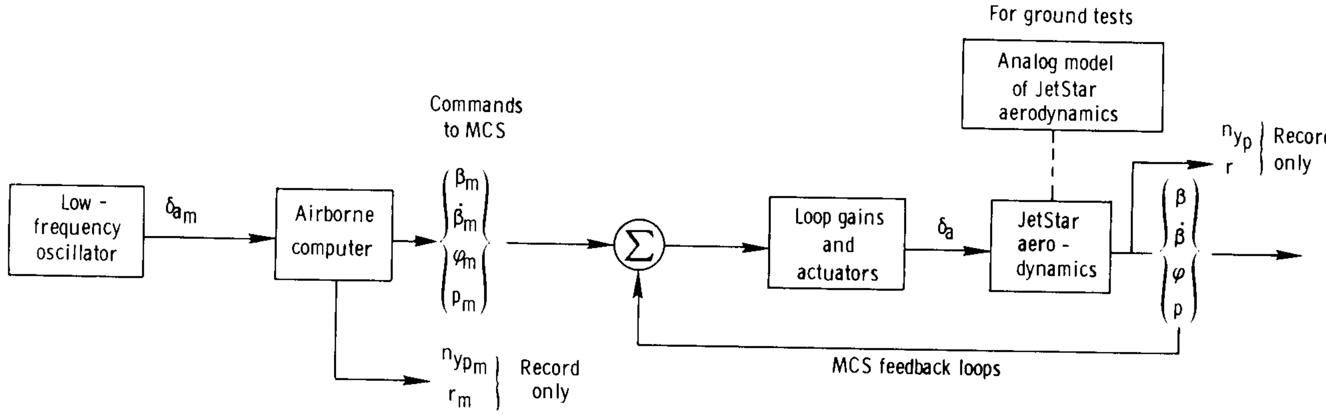


Figure 13. Test setup for model-following frequency responses.

All the frequency-response plots discussed in the following sections were obtained by exciting the Mach 2.35 XB-70 model with aileron inputs. These results are believed to be more pertinent to the GPAS validation program than the frequency responses generated by rudder excitation. In general, the two results will not be the same.

Bode diagrams of directly matched variables. – Figure 14 shows the amplitude ratio and phase for $\frac{p_J}{p_m}(\omega)$. The ground and flight results agree well; the magnitudes are

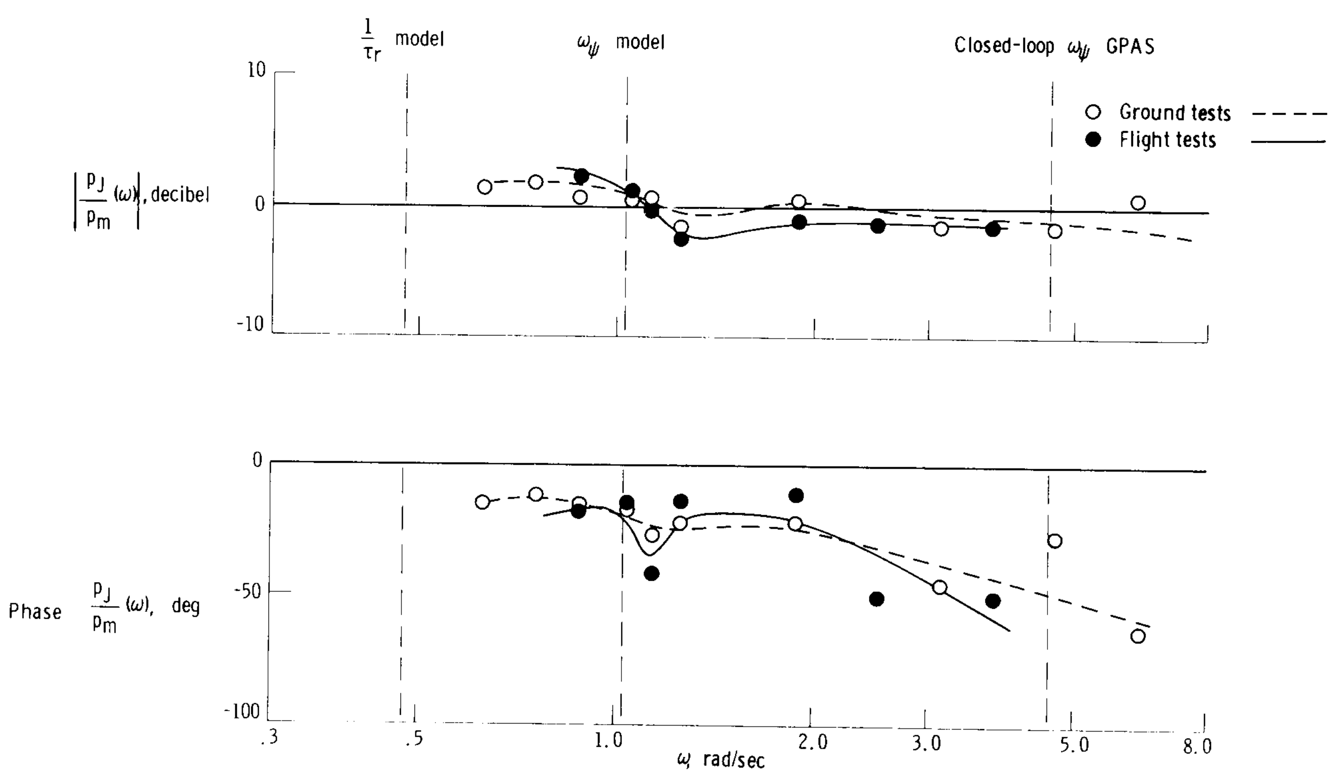


Figure 14. Frequency response of roll-rate model-following. XB-70 model; Mach 2.35.

within 2 decibels and the phase angles within 15°. It would appear then that the roll-following channel could be set up and adjusted on the ground. Model-following is shown to be good in this figure. The model roll mode and Dutch roll mode root locations are indicated in the Bode plot, as is the closed-loop Dutch roll root. At the natural frequencies, the model-following amplitude error is 2 decibels or less, and the phase lags are on the order of 15° to 20°. At these frequencies, the equivalent time lag is about 0.3 second. The dip in phase lag at $\omega = 1.15$ rad/sec is equivalent to a 0.6-second time lag. A long GPAS time history of a pilot evaluation was sampled periodically, and the lag between p_m and p_J was measured. The results are displayed in a histogram in figure 15. The lags measured form a distribution centered around 0.3 and 0.4 second, indicating that, as expected, most of the aircraft roll motion occurred around the model Dutch roll natural frequency.

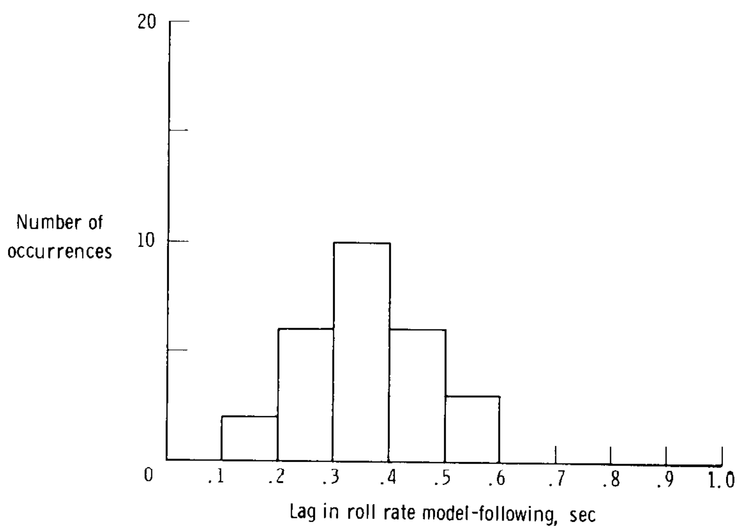


Figure 15. Histogram of roll rate model-following time lags for Mach 2.35 XB-70 simulation.

Figure 16 shows the results of ground and flight frequency responses for sideslip model-following. The agreement between the two sets of data is good at and below the model Dutch roll frequency. The

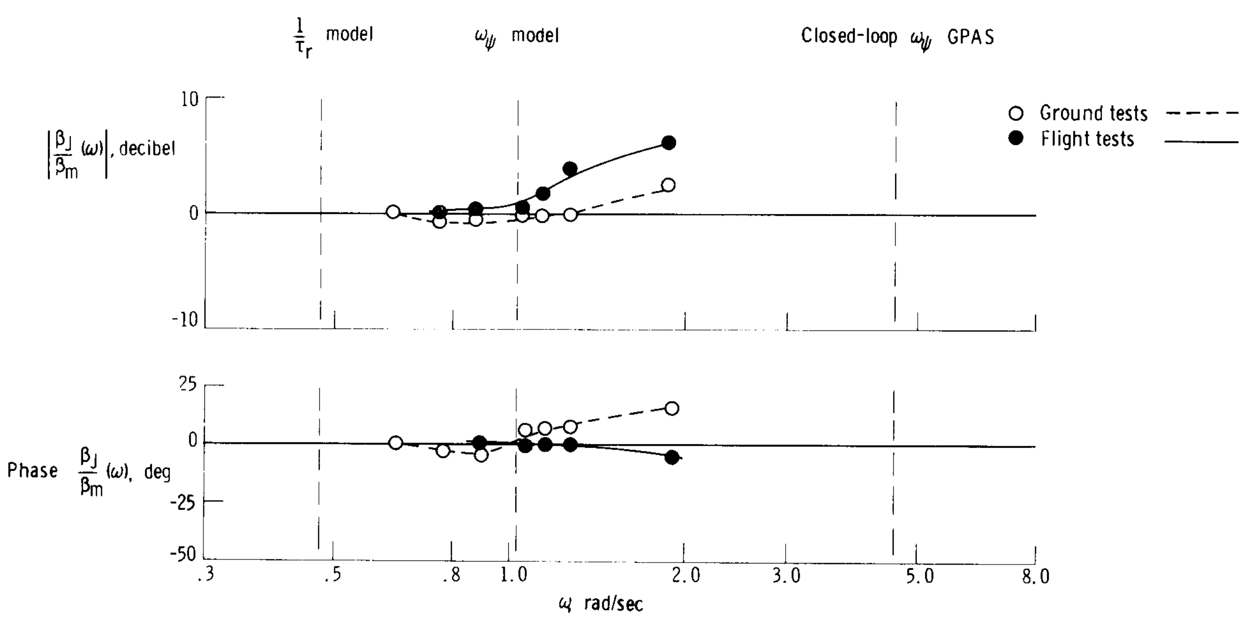


Figure 16. Frequency response of sideslip model-following. XB-70 model; Mach 2.35.

ground amplitude ratio data appear to be slightly optimistic, in that the flight data show a larger amplitude error. Data for higher frequencies were not included because the amplitudes had diminished considerably, which made measurements difficult. Near the model's natural frequency, model-following is excellent, with very small amplitude and phase errors. This is also evident in time histories shown in reference 1.

Bode diagrams for uncontrolled variables.—Any response variable of the JetStar that is not being forced to follow the corresponding model quantity is considered to be uncontrolled, even though it is dependent on what is being matched. No independent means are available to match both sideslip and yaw angle, for example, because only a rudder surface is available; hence, if sideslip is a directly matched parameter, yaw angle or yaw rate is an uncontrolled variable. The two uncontrolled variables considered in this section are yaw rate and lateral acceleration at the pilot's location.

The frequency response of yaw-rate model following is shown in figure 17. As for roll rate and sideslip, the ground and flight-test results show fair correlation over the

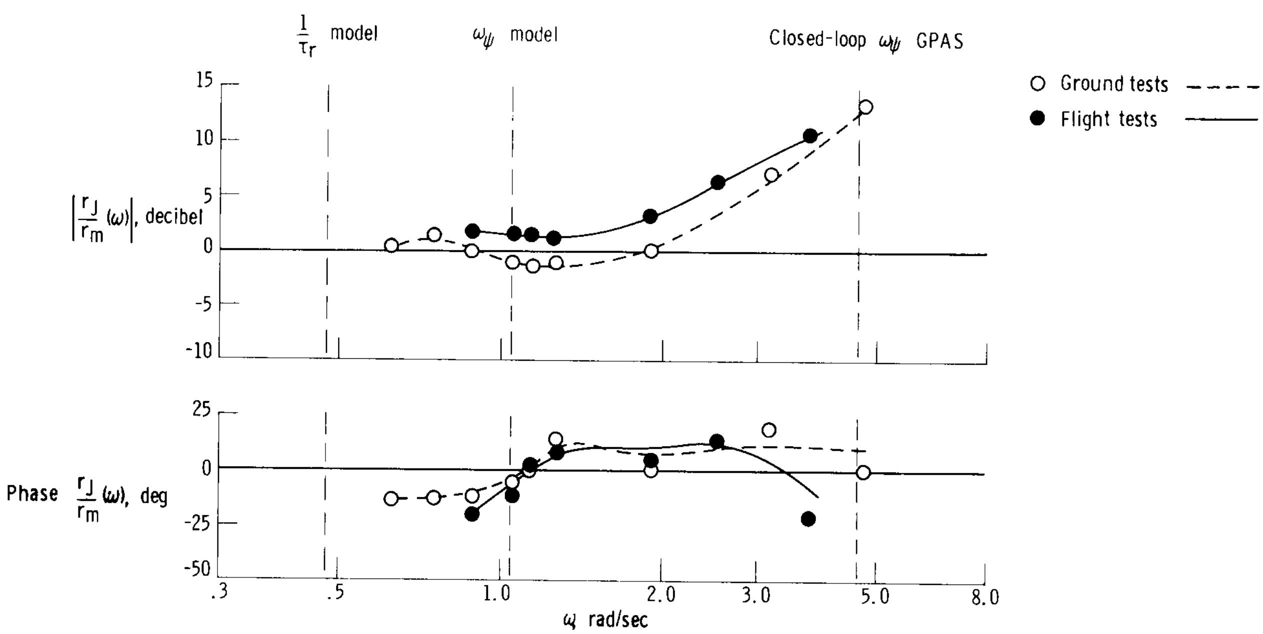
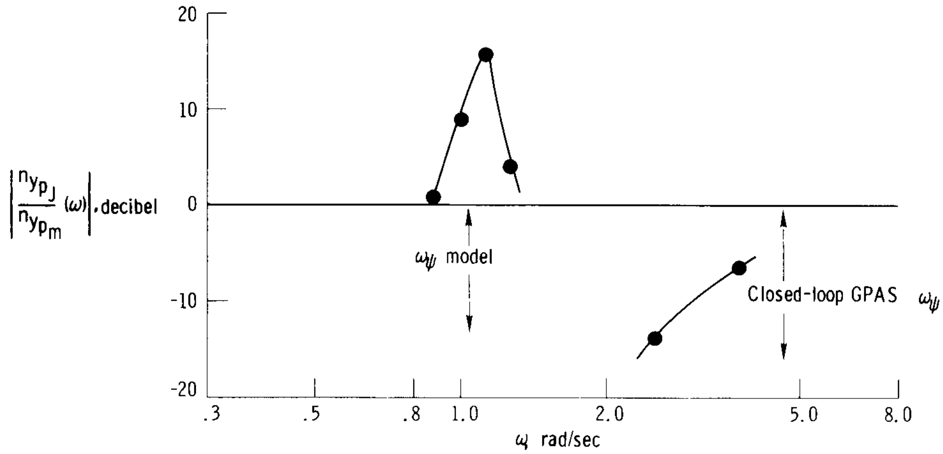


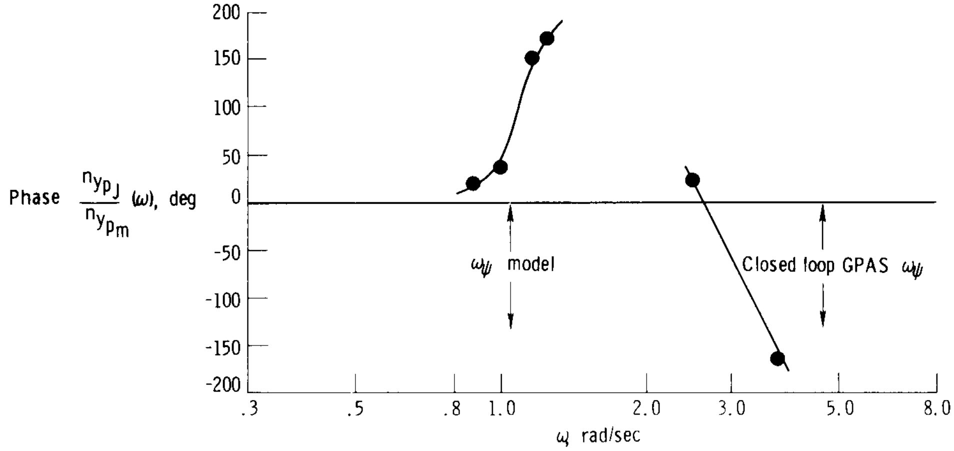
Figure 17. Frequency response of yaw-rate model-following. XB-70 model; Mach 2.35.

midfrequency range. This is not entirely unexpected, because $\dot{\beta}_m \cong -r_m$ in the Dutch roll, and β_m is followed directly with little error. If data had been taken at lower frequencies, a large static error would have resulted, because the steady yaw rate in a turn is a function of true airspeed, a quantity which the JetStar did not simulate in this instance. Accurate model-following of sideslip, then, results in good duplication of yaw-rate response at model Dutch roll frequencies.

Pilot lateral-acceleration matching is shown in figures 18(a) and 18(b). Only the flight data are shown. The amplitude ratio and phase angle of $\frac{n_{y_{p_J}}(\omega)}{n_{y_{p_m}}}$ are highly



(a) Amplitude ratio.



(b) Phase angle.

Figure 18. Frequency response of pilot lateral acceleration model-following obtained during flight test. XB-70 model; Mach 2.35.

variable throughout the measured frequency range. Pilot lateral-acceleration matching is a sensitive function of pilot aileron control frequency content. For example, near the model Dutch roll frequency, a change of 0.30 rad/sec in driving frequency results in a 15-decibel change in amplitude ratio and a 150° change in phase angle. In general, then, it would be expected that for an arbitrary pilot input, n_{y_p}-following would be poor.

OPERATIONAL EXPERIENCE WITH THE MODEL-CONTROLLED SYSTEM

Operation in Turbulence

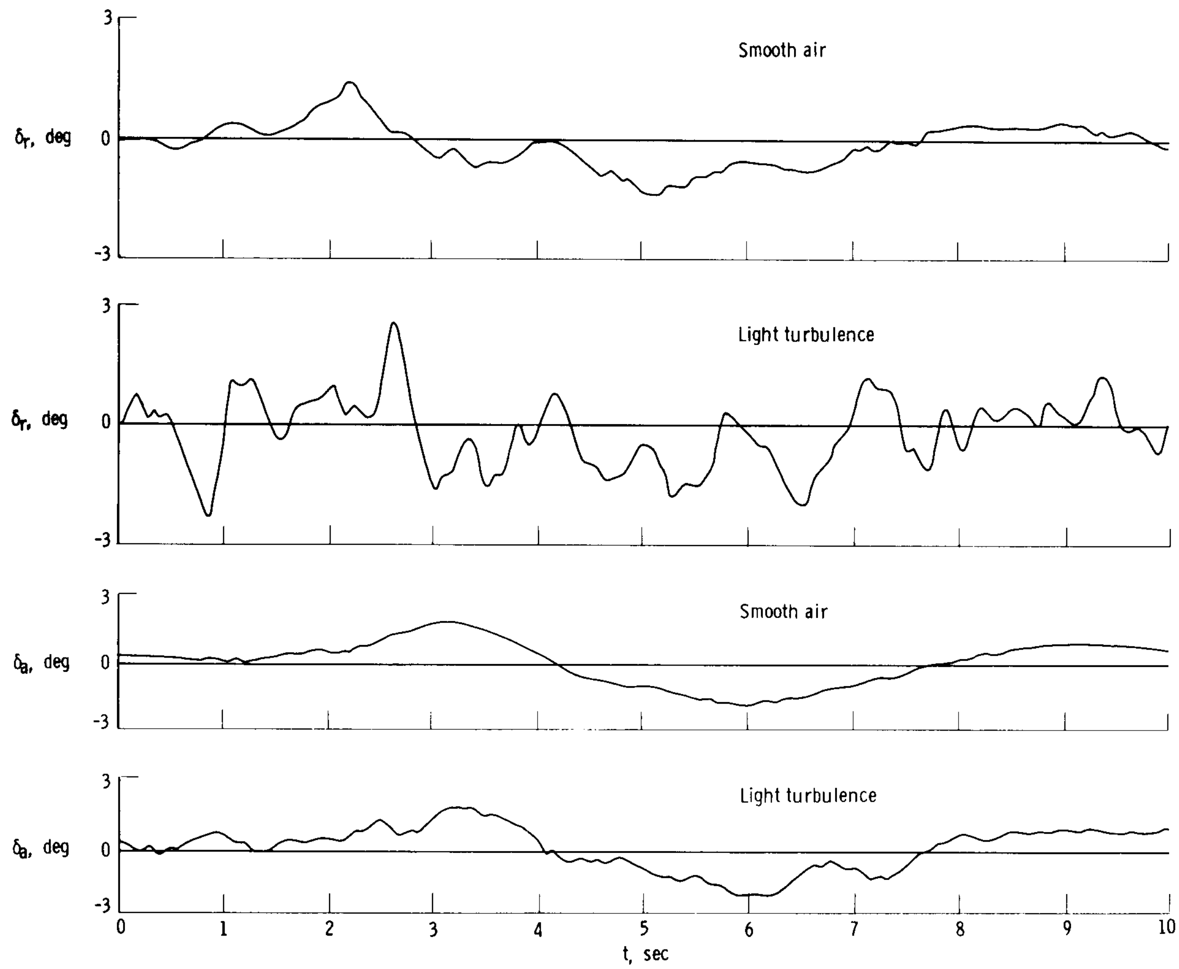
With the feedback gains listed in table 2, operation of the GPAS in turbulence any greater than light was impossible. Control surface chatter due to normal- or lateral-acceleration peaks and frequent automatic system disengagements due to exceeding the acceleration threshold occurred when operation was continued in rough air. Figures 19(a) and 19(b) show JetStar control surface activity and response in "smooth air and light turbulence" (pilot's description). The model response is identical in both instances. Although the model Dutch roll response was still being followed, the high-frequency noise was greatly increased in light turbulence. JetStar rudder activity increased considerably, but aileron motion remained reasonably smooth in this turbulence level. It is obvious that the basic JetStar and XB-70 airframe response would differ if both vehicles were flown through the same turbulence. Differences in wing loading, size, speed, and bending modes are causal factors in determining response to turbulence. In addition, the JetStar has aerodynamic feedback loops which alter the basic JetStar response to turbulence. For example, if an atmospheric disturbance caused the JetStar to roll from level flight, the model-following system would sense the attitude change as an error because the computer model is not influenced by natural turbulence. The JetStar would then be commanded to return to level flight through the control system. In turbulence, of course, this corrective action is continuous, resulting in JetStar motions obviously not those of the XB-70 model or the unaugmented JetStar. Thus the GPAS did not provide realistic XB-70 rough-air simulation while operating in rough air. Most of the GPAS flight time during the validation program was in smooth air. No attempt was made to reproduce the structural response prevalent in the XB-70 cockpit.

JetStar Flight-Path Control

As previously discussed, only α_m and $\dot{\alpha}_m$ were matched by the GPAS in the longitudinal mode. No direct control was exerted over JetStar forward or vertical velocity during these validation simulations. Thrust commands by the pilot to the analog computer were made with a simulated throttle. Thus the model velocity and vertical speed changes were reflected in the evaluation pilot's instrument readings, but there were no associated changes in JetStar forward or vertical speed. The only changes in these two JetStar quantities resulted from the angle-of-attack variations commanded by the model.

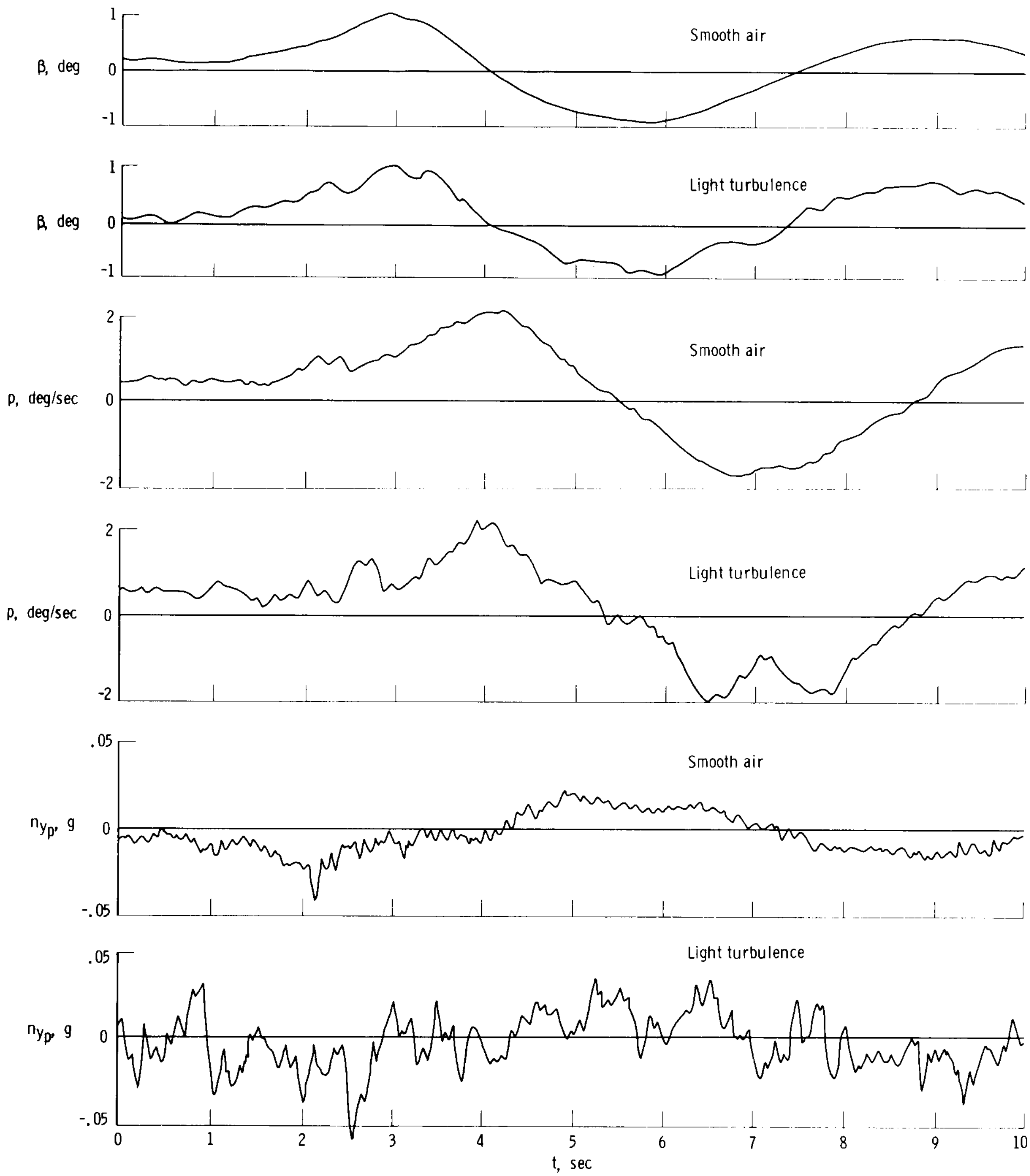
Over long times, it might be expected that JetStar velocity and altitude would drift from the initial trim value of 250 knots indicated airspeed at 6096 meters (20,000 feet) altitude, but this generally did not pose any serious operational problems. The JetStar had to be trimmed carefully before the variable-stability system was engaged, but when this was done it was not unusual to find the JetStar within 5 knots indicated airspeed and 305 meters (1000 feet) altitude of the trim condition after the GPAS had been engaged for as long as 30 minutes. This resulted partly from the fact that a cruise condition was being simulated, and no large model flight condition changes were commanded.

Early in the validation program a velocity model-following loop was used; the JetStar throttles were used to follow ΔV_m and $\Delta \dot{V}_m$ changes in velocity from trim. Generally, the model-following performance was satisfactory. The use of the throttle loops was abandoned, however, because the pilots considered JetStar throttle movements during the evaluation to be distracting; throttle lever movements did not necessarily correspond to simulated thrust commands to the model. The lack of duplication of model flight-path changes with no throttle loops operating was far less noticeable to the pilots than the distracting JetStar throttle motions which occurred when velocity was being matched.



(a) JetStar control surface activity.

Figure 19. Model-following control system operation in smooth air and in light turbulence for identical model inputs. JetStar at Mach 0.55 and 6100 meters (20,000 feet).



(b) JetStar response.

Figure 19. Concluded.

CONCLUSIONS

On the basis of flight time histories and pilot comments and ratings given during the validation of the general purpose airborne simulator (GPAS), the following conclusions were drawn concerning the effect of motion and visual cues on the simulation fidelity:

1. Lateral acceleration at the pilot's location was poorly duplicated in the GPAS for the Mach 1.2 XB-70 condition. However, for this condition, which was relatively well behaved (NASA TN D-6431), it appeared that the mismatch in pilot lateral acceleration was of little consequence. Sensitivity tests showed that moderate variations in directional motion produced insignificant changes in pilot opinion of the vehicle handling qualities.

2. A fixed-base simulation would have adequately simulated the Mach 1.2 XB-70 condition for handling-qualities research.

3. Lateral acceleration at the pilot's location was duplicated fairly well in the GPAS for the Mach 2.35 XB-70 condition at or near the Dutch roll natural frequency as a result of favorable aerodynamic and geometric characteristics.

4. For the Mach 2.35 XB-70 condition, which exhibited a moderate PIO tendency, the pilot appeared to be sensitive to directional-cue variations in the GPAS. The pilot-observed worsening of vehicle handling qualities with the addition of motion and visual cues to a nonmoving simulation demonstrated cue effects different from those which had been observed in other motion simulations.

5. A high-quality motion simulation was required to represent the Mach 2.35 condition adequately from a handling-qualities standpoint.

6. Motion or visual cue mismatches, or both, may have contributed to the discrepancy in required Dutch roll damping for the Mach 2.35 simulation reported in NASA TN D-6431 because of the sensitivity of the pilot-induced-oscillation condition to the simulator configuration.

7. The use of scaled sideslip-following was useful in determining pilot sensitivity to directional motion cues.

In addition to achieving the primary goals in the GPAS validation program, much experience was obtained in operating and setting up the airborne simulator. The following conclusions were reached:

1. Conventional model-following gain selection techniques yielded satisfactory model-following performance for parameters selected to be matched.

2. Model-following frequency responses taken during ground and flight tests showed the ground simulation to be generally optimistic concerning simulation fidelity. In addition, the model-following frequency responses were found to be generally sensitive functions of frequency.

3. Velocity model-following was not necessary in the cruise simulations considered in the validation program.

4. It was not possible to operate the GPAS in turbulence greater than very light because of the feedback gains used in the validation flights.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., June 1, 1971.

APPENDIX A

PILOT COMMENTS ON CUES EXPERIMENT CONDITIONS FOR THE MACH 2.35 XB-70 CONDITION

Case 1 - IFR, No Motion

Roll power certainly adequate.

I don't feel as though I have as much aileron, or lateral centering, as I had with the airplane engaged (VFR, full motion). I seem to have more of a tendency to wander around the wings-level position without noticing that I have done this.

The double aileron pulse gives me the same impression as it did with the airplane engaged (VFR, full motion), but I am aware of not having visual and motion cues. With the airplane engaged, I didn't think much about the seat-of-the-pants cues, but I kind of grope for them to come in here.

The realism of the simulation is definitely affected by the motion or lack of it.

It seems the PIO difference is the greatest difference here. There is no question in my mind that the PIO is easier to get started with the aircraft engaged (VFR, full motion). It seems that by having the horizon visible, I detect it quicker when it starts to roll off, and I start to do something about it. Of course, that tends to set the PIO off.

If I were evaluating this condition fixed base, without the actual horizon, I would not have picked up the problem with the PIO that definitely exists with the airplane engaged.

One other thing, when flying fixed base, I have a greater feeling of confidence in going to steep bank angles than I do when the airplane is engaged.

It's noticeably easier to stop the PIO if it gets going here. It's easier to fly this case from the standpoint of PIO.

I would rate this case as a 4. It's not a bad flying machine.

Case 2 - IFR, $\frac{\beta_J}{\beta_m} = 0$

Roll power is adequate.

I can feel some seat-of-the-pants cues, but it's not getting through to me as strong as it did with the visual condition (VFR, full motion).

The PIO is not as apparent to me as it was when I was looking out the window. There is some PIO here - a little more than with the aircraft disengaged (IFR, no motion): I get the PIO and I see the sideslip indicator oscillating, but I'm not so much aware of it here. It certainly doesn't bother me as much.

I would rate this case as a 4 1/2.

Case 3 - IFR, Full Motion

There is more PIO connected with this case than with the disengaged case (IFR, no motion).

I can't tie down exactly what causes it, except that I find myself oscillating laterally a little more than I should, and I can feel it as well.

Roll power and adverse yaw - no real difference.

I can't see a whole lot of difference between this and the VFR case (VFR, full motion) except that I don't have quite the same tendency to PIO as I do VFR, but it's pretty close.

I would rate this case a 5, downrating primarily because of the PIO tendency.

Case 4 - VFR, $\frac{\beta_J}{\beta_m} = 0$

Ample roll power.

Adverse yaw may be a little less than the reference case (VFR, full motion).

PIO tendency reduced from reference case.

It seems to me that you have cut down the side force to the cockpit. I don't seem to experience quite the PIO laterally as I had in the reference case.

It seems that Dutch roll damping may be a little better here.

Rating of this case is 4.

It also seems like you get a little less lateral movement here - and that may be just due to the fact that I am not feeling much side force - but I do get the impression of less rolling here.

Case 5 - VFR, Full Motion

Roll power is very good.

Adverse yaw due to aileron is moderate.

This has a moderate PIO tendency that is slightly worse than all the other conditions, and I would rate this a 5 1/2.

Any time the pilot is in the loop you tend to set up an oscillation. I generate $\pm 1°$ of sideslip. This condition is a resimulation of the case which I feel represents the XB-70 pretty well.

This condition is only slightly worse VFR than it is IFR. I pick up the yaw and banking a little faster looking outside and apparently tend to couple with it a little more.

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